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

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T10: Searches for New Physics
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Prospects for exotic light scalar measurements...

Outline:

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

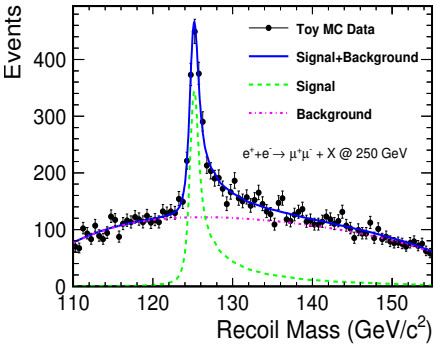
Work carried out in the framework of the ILD concept group
as a contribution to the ECFA e^+e^- Higgs/EW/top factory study

All presented results are "work in progress"...

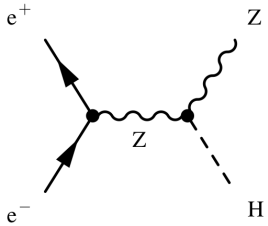
Motivation

e^+e^- Higgs factory

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



In the ZH production channel (dominant below 450 GeV) we can use "Z-tagging" for unbiased selection of events.



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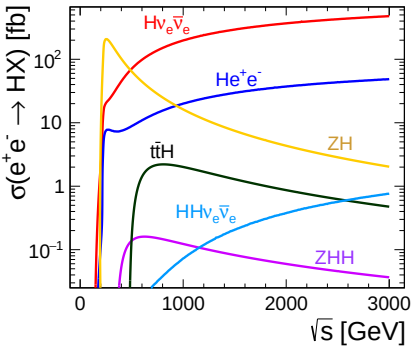


In the ZH production channel (dominant below 450 GeV) we can use "Z-tagging" for unbiased selection of events.

New channels open at higher energies allowing for direct access to top Yukawa coupling and Higgs self-coupling.

Precision Higgs boson, top quark and electroweak measurements will result in indirect constraints on BSM or possible hints...

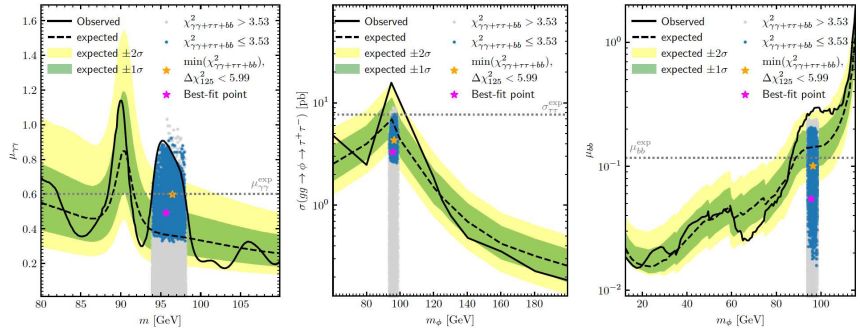
But additional, light exotic scalar states are still not excluded by the existing data!

see also contribution #565 (Tania Robens in joint T09+T10 session)

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 $\tau\tau$...

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



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

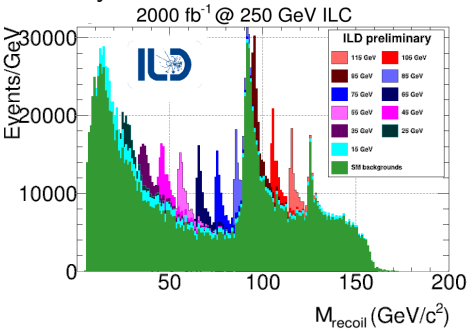
see also contribution #529 (Thomas Biekötter in joint T09+T10 session)

Previous studies

New scalars could be produced in the process similar to Higgs-strahlung

Prospects for their observation only partially explored so far...

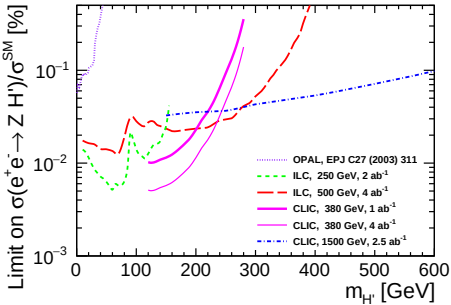
ILD study arXiv:1903.01629 arXiv:2005.06265



Search independent on the scalar decay:

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

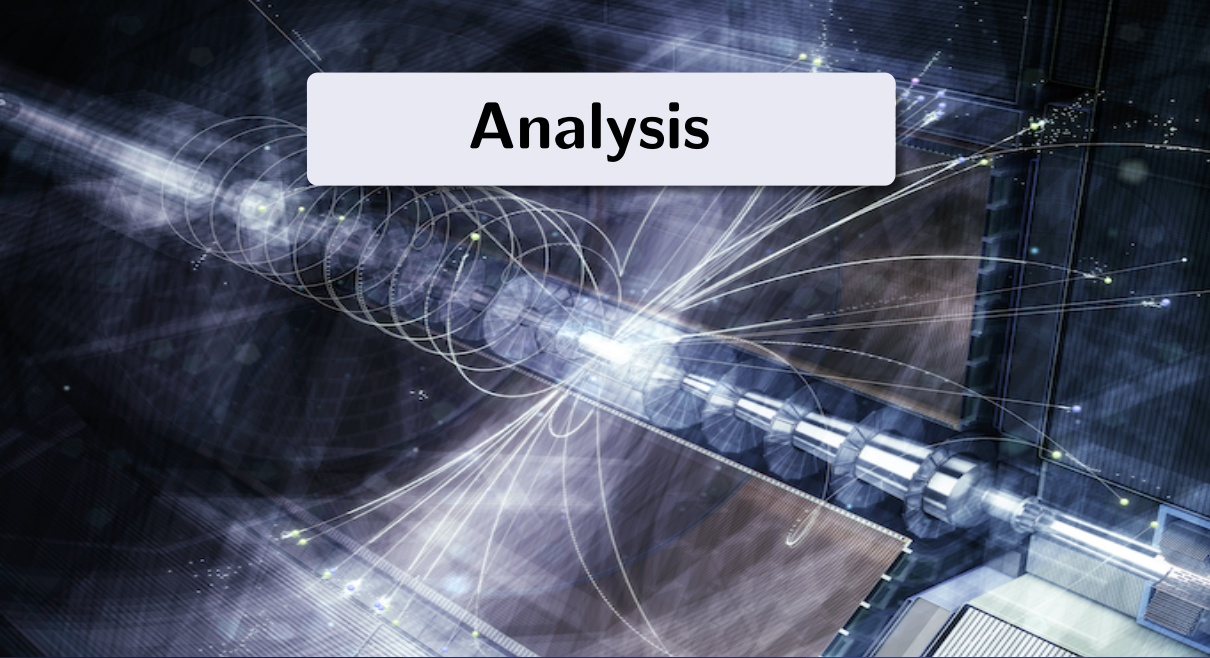
Expected sensitivities of ILC and CLIC



CLIC search assuming invisible decays

arXiv:2002.06034 arXiv:2107.12730

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

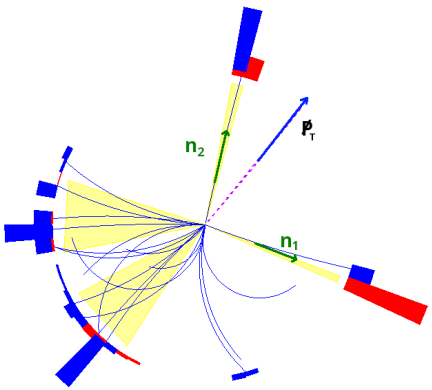
Integrated lumionsity of $2 \times 900\,\text{fb}^{-1}$, with $-80\%/+30\%$ and $+80\%/-30\%$ polarisation.

Fast detector simulation with Delphes ILCgen model.

Tau reconstruction

arXiv:1509.01885

Example signal event with hadronic tau decays



Tau leptons are very boosted $\Rightarrow$ collinear approximation

Assume tau neutrinos are emitted in the tau jet direction.

Their energies can be found from transverse momentum balance:

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

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

Unique solution !

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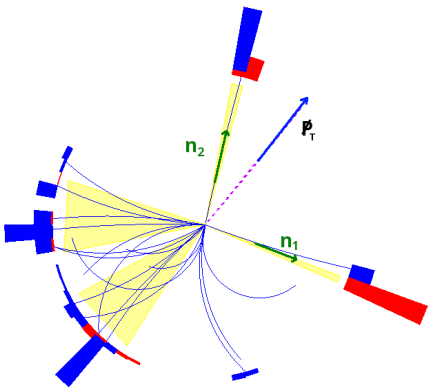

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where $\vec{n_1}$ and $\vec{n_2}$ are directions of the two tau jets.

Unique solution !

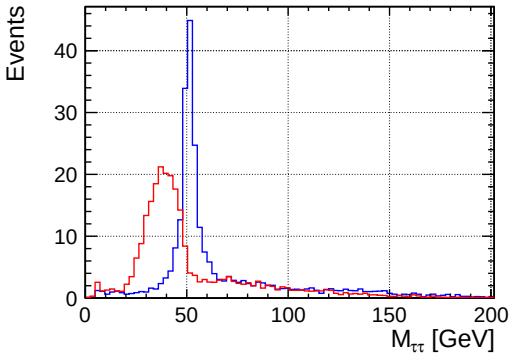
Works also for semi-leptonic and leptonic events!

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

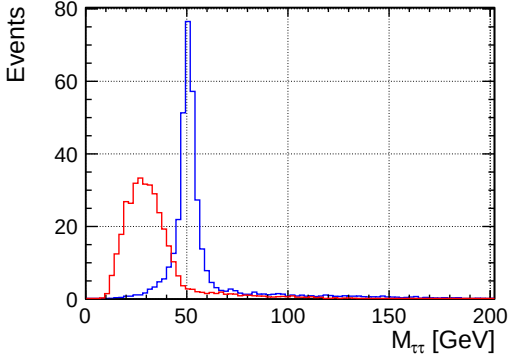
Tau reconstruction

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

Hadronic events (two tagged jets)



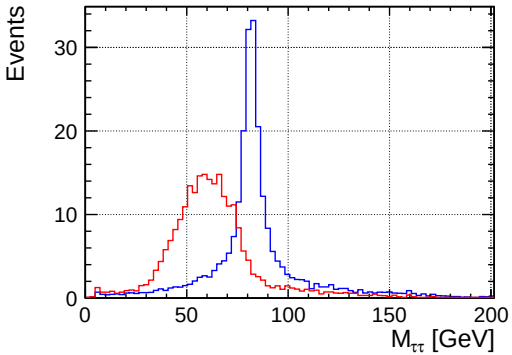
Semi-leptonic events (lepton and one tagged jet)



Tau reconstruction

Distribution of the raw and corrected mass of the tau candidate pair for $M_S = 80\,\text{GeV}$

Hadronic events (two tagged jets)



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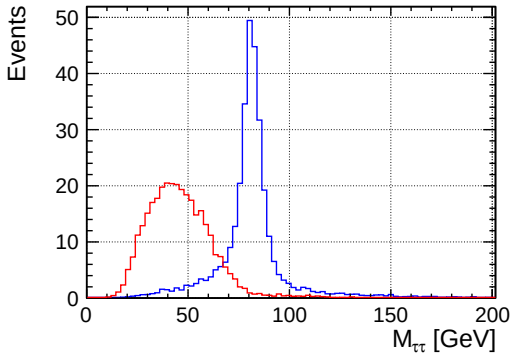
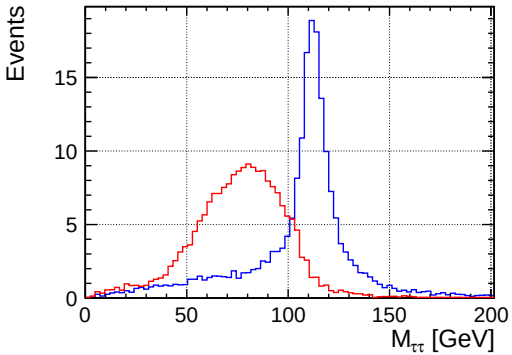


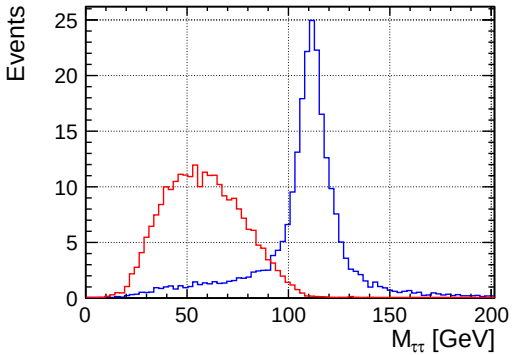
Tau reconstruction

Distribution of the raw and corrected mass of the tau candidate pair for $M_S = 110\,\text{GeV}$

Hadronic events (two tagged jets)



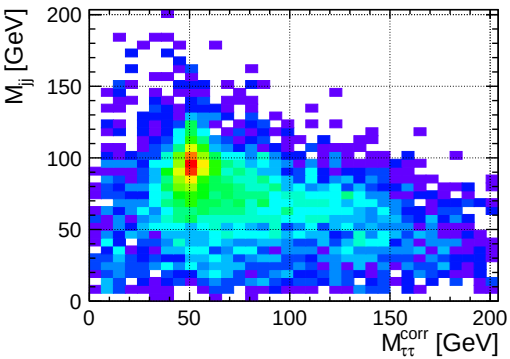
Semi-leptonic events (lepton and one tagged jet)



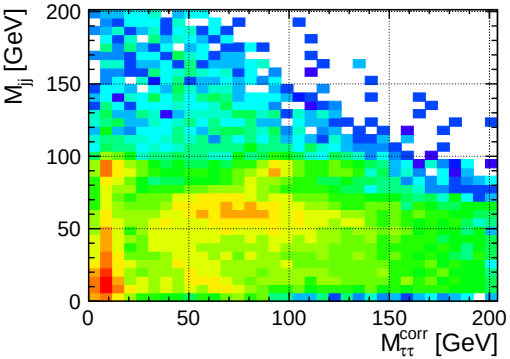
Kinematic distributions

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

Hadronic signal events



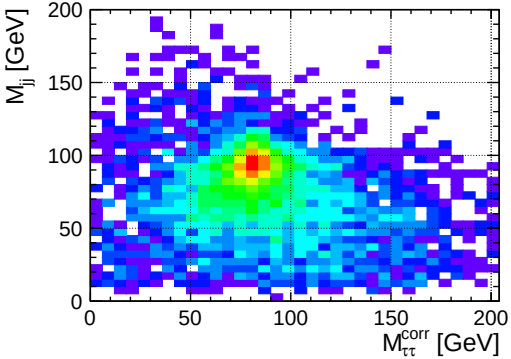
Background events



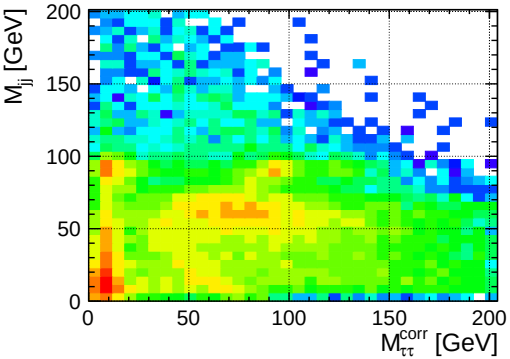
Kinematic distributions

Distribution of the reconstructed Z boson and scalar masses for $M_S = 80\,\text{GeV}$

Hadronic signal events



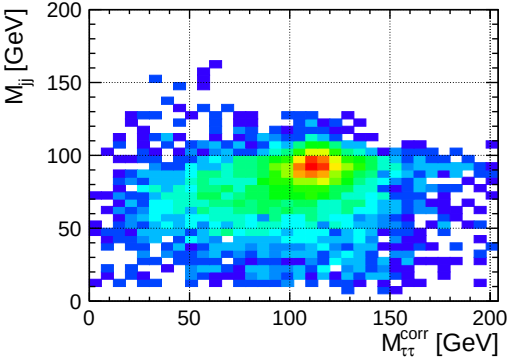
Background events



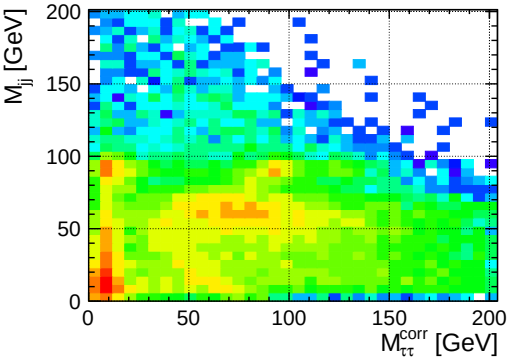
Kinematic distributions

Distribution of the reconstructed Z boson and scalar masses for $M_S = 110\,\text{GeV}$

Hadronic signal events



Background events

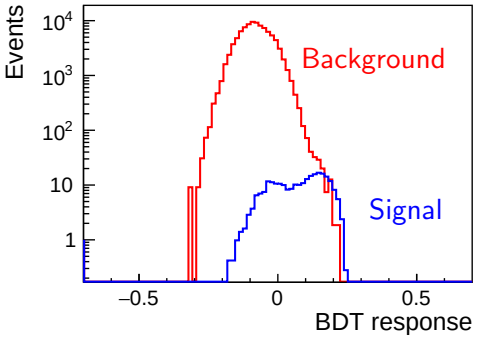


Signal event selection

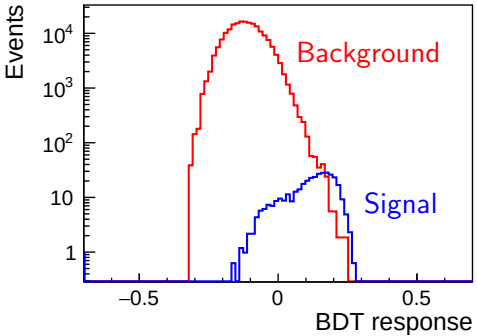
see backup slides for list of BDT input variables

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

Hadronic events

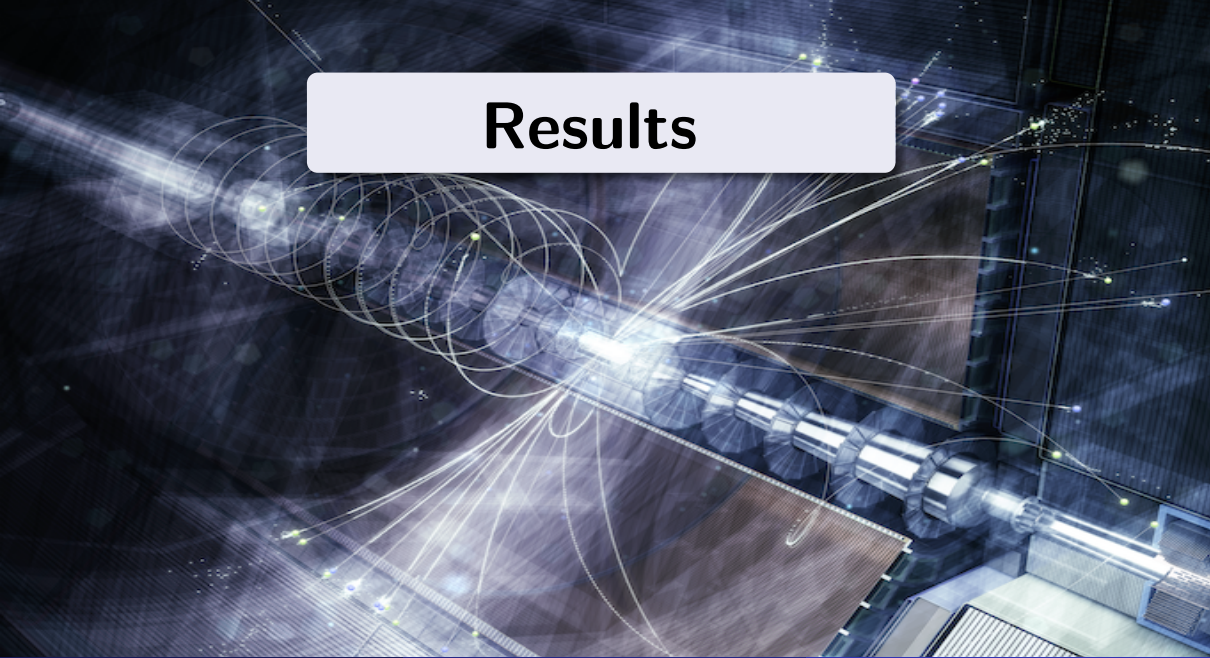


Semi-leptonic events



Signal normalized to $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)/\sigma_{SM} = 1\%$ $\quad +80\%/-30\%$ polarisation

Results



Results

Two analysis scenarios

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

Two analysis scenarios

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Limit setting approach

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

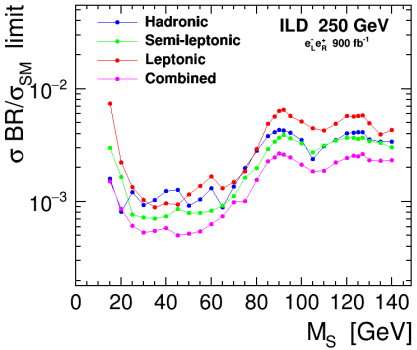
$$\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)/\sigma_{SM}(M_S) \;=\; 1\%$$

95% CL cross section limit was then calculated as the signal cross section corresponding to the significance of 1.64 (with the fixed BDT response cut)

Cross section limits for loose selection

Cross section limits with BDT response cut (optimized for significance at 1% signal level)

Running with $-80\%/+30\%$ polarisation



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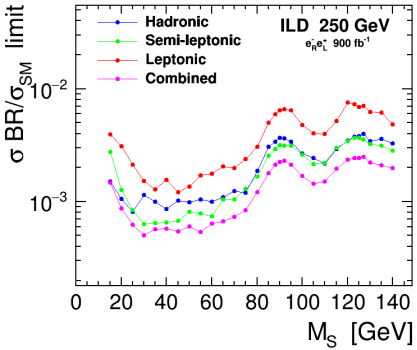
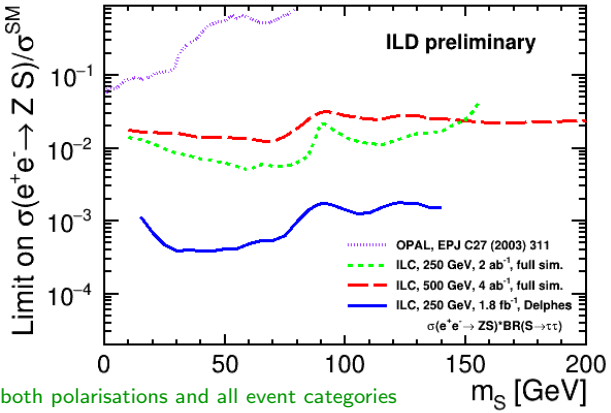


Tighter cross section limits with loose selection

Cross section limits for loose selection

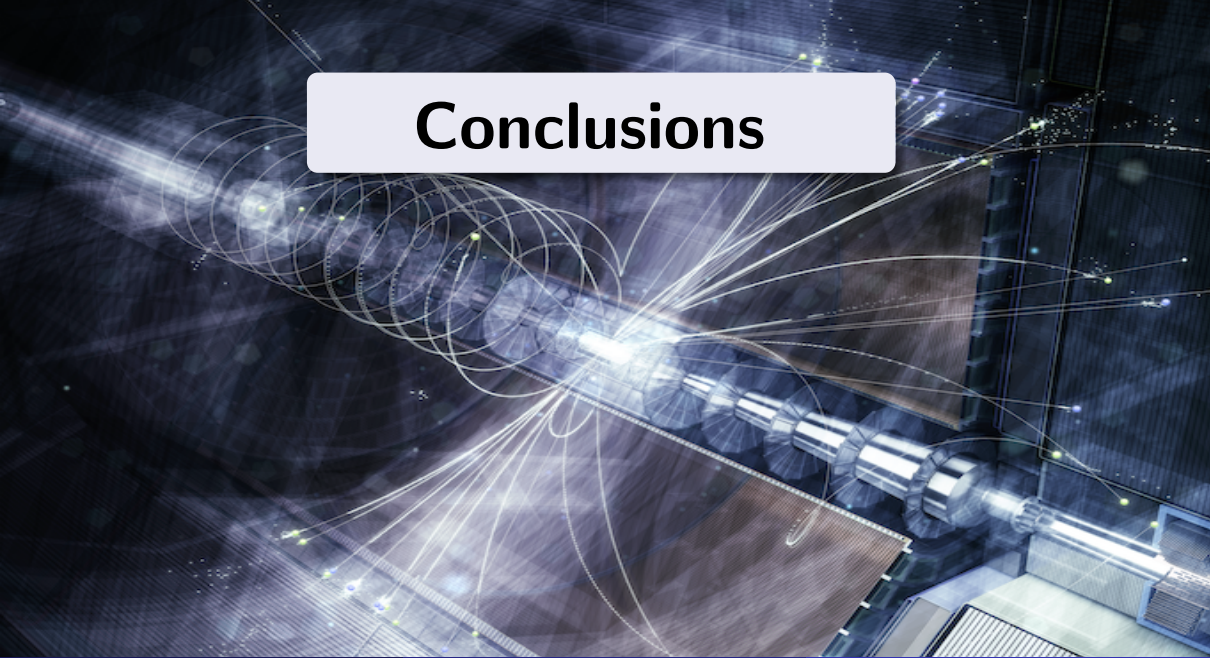
Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)$
compared with decay independent limits from earlier studies



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

One BDT trained for both polarisations and all event categories

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...

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Order of magnitude limit improvement already with the very simple limit setting approach
Should improve further when properly combining results from different event samples.

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

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Comparison with full simulation needed to confirm the results...

Other decay channels of the light scalar still to be explored !
One of the focus topics in the ECFA study towards an e^+e^- Higgs/EW/top factory
you are welcome to join!


Thank you!

ECFA studies towards an e^+e^- Higgs/EW/top factory

Three working groups of the ECFA study are intended to:

- bring together communities & activities
- explore synergies between projects
- address the challenges

A set of "focus topics" have been defined in the Physics Potential working group (WG1) to point to concrete examples of work still to be done. These topics should help to bring people together (across projects) and to attract more people (e.g. LHC) into the e^+e^- community.

One of the focus topics proposed within the "direct search" subgroup (WG1-SRCH) are

"New exotic scalars (EXscalar)"

N2HDM scenario

arXiv:2203.13180

Parameters of the best-fit point (minimal value of χ^2) $\Rightarrow$ **BP1**

$\Rightarrow$

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	
$\mathrm{BR}^{bb}_{h_1}$	$\mathrm{BR}^{gg}_{h_1}$	$\mathrm{BR}^{cc}_{h_1}$	$\mathrm{BR}^{\tau\tau}_{h_1}$	$\mathrm{BR}^{\gamma\gamma}_{h_1}$	$\mathrm{BR}^{WW}_{h_1}$	$\mathrm{BR}^{ZZ}_{h_1}$
0.005	0.348	0.198	0.412	$6.630 \cdot 10^{-3}$	0.025	$3.382 \cdot 10^{-3}$
$\mathrm{BR}^{bb}_{h_2}$	$\mathrm{BR}^{gg}_{h_2}$	$\mathrm{BR}^{cc}_{h_2}$	$\mathrm{BR}^{\tau\tau}_{h_2}$	$\mathrm{BR}^{\gamma\gamma}_{h_2}$	$\mathrm{BR}^{WW}_{h_2}$	$\mathrm{BR}^{ZZ}_{h_2}$
0.553	0.085	0.032	0.069	$2.537 \cdot 10^{-3}$	0.228	0.028
$\mathrm{BR}^{tt}_{h_3}$	$\mathrm{BR}^{bb}_{h_3}$	$\mathrm{BR}^{\tau\tau}_{h_3}$	$\mathrm{BR}^{h_1h_1}_{h_3}$	$\mathrm{BR}^{h_1h_2}_{h_3}$	$\mathrm{BR}^{h_2h_2}_{h_3}$	$\mathrm{BR}^{WW}_{h_3}$
0.123	0.739	0.000	0.002	0.072	0.030	0.022
BR^{tt}_{A}	BR^{bb}_{A}	$\mathrm{BR}^{\tau\tau}_{A}$	$\mathrm{BR}^{Zh_1}_{A}$	$\mathrm{BR}^{Zh_2}_{A}$	$\mathrm{BR}^{Zh_3}_{A}$	$\mathrm{BR}^{WH^\pm}_{A}$
0.053	0.173	0.000	0.024	0.001	0.015	0.734
$\mathrm{BR}^{tb}_{H^\pm}$	$\mathrm{BR}^{\tau\nu}_{H^\pm}$	$\mathrm{BR}^{Wh_1}_{H^\pm}$	$\mathrm{BR}^{Wh_2}_{H^\pm}$			
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: no $b\bar{b}$ decays, $\tau^+\tau^-$ decays dominate...

Signal event selection

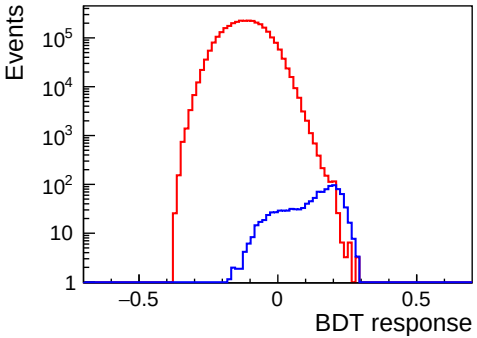
Selection based on BDT classifier trained with following input variables:

- 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
- event category and polarization flags

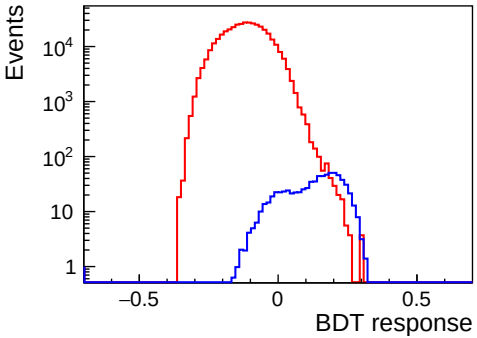
Signal event selection

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

Running with $-80\%/+30\%$ polarisation



with $+80\%/-30\%$ polarisation

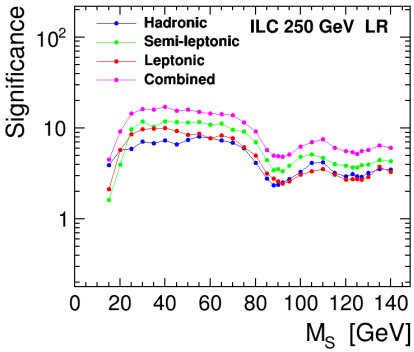


One BDT trained for all event categories

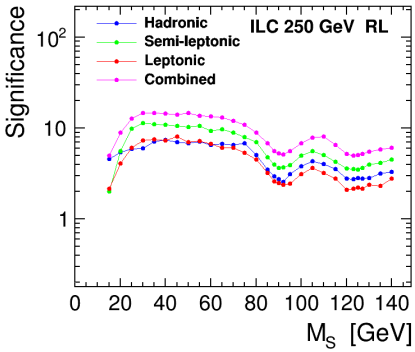
Significance for tight selection

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

Running with $-80\%/+30\%$ polarisation



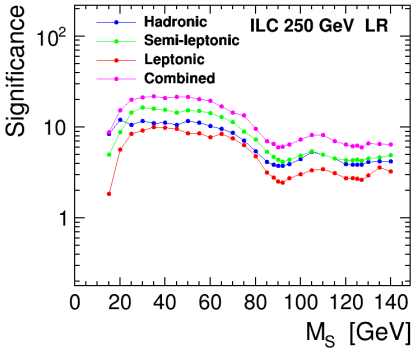
with $+80\%/-30\%$ polarisation



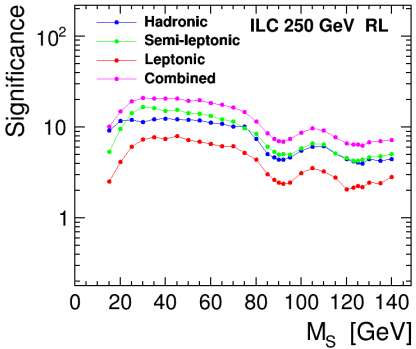
Significance for loose selection

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

Running with $-80\%/+30\%$ polarisation



with $+80\%/-30\%$ polarisation



Loose selection results in higher significance

BDT selection

Selection results for **hadronic events** (loose selection), signal hypothesis with $M_S = 50\,\text{GeV}$.
Runs with two polarisations combined ($2 \times 900\ \text{fb}^{-1}$).

Sample	N_{pres}	N_{BDT}	ε_{BDT} [%]
Signal (1%)	3190	588	18.4
$qq\tau\tau$	107000	385	0.36
$qqqq$	1730000	143	0.008
$qqll$	247000	18.3	0.007
$qq\tau\nu$	2350000	6.8	0.0003
$qql\nu$	1290000	—	—
Total bg.	5729000	554	

N_{pres} - events expected after preselection, N_{BDT} - after optimized BDT response cut

BDT selection

Selection results for **semi-leptonic events** (loose selection), for signal with $M_S = 50\,\text{GeV}$.
Runs with two polarisations combined ($2 \times 900\ \text{fb}^{-1}$).

Sample	N_{pres}	N_{BDT}	ε_{BDT} [%]
Signal (1%)	2880	979	33.9
$qq\tau\tau$	64700	919	1.4
$qqll$	337000	117	0.035
$qq\tau\nu$	1250000	106	0.008
$qql\nu$	8770000	44	0.0005
$qqqq$	2070	7.1	0.34
Total bg.	10430000	1193	

N_{pres} - events expected after preselection, N_{BDT} - after optimized BDT response cut