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

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on the High Energy Circular Electron Positron Collider
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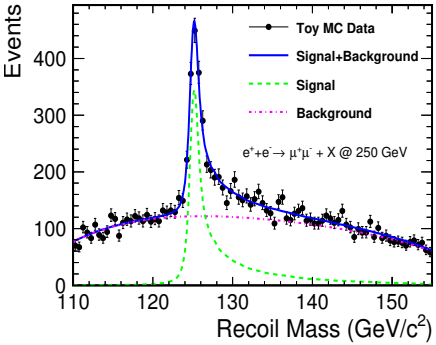
Prospects for light exotic scalar measurements

Outline:

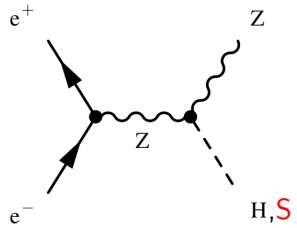
1. Motivation
2. ILC and its experiments
3. Analysis framework
4. Results
   - $S \to \tau^+\tau^-$
   - $S \to$ invisible
   - $S \to b\bar{b}$
5. Ongoing studies
6. Conclusions

e^+e^- Higgs factory

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



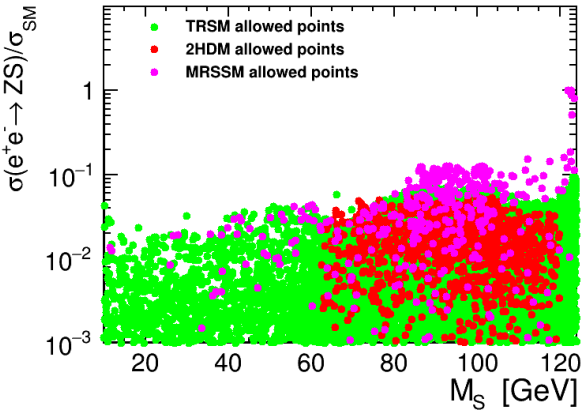
At 240 – 250 GeV we will focus on H_{125} production



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

Possible scenarios (presented at ECFA'2023 workshop)

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

ECFA study

Light scalar searches at future Higgs Factories were only partially studied so far.

More work is clearly needed to understand the experimental challenges and prospects.

Light scalar searches were selected as one of the ECFA study focus topics arXiv:2401.07564

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Theoretical and phenomenological targets (1)

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

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

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 also be explored.

Theoretical and phenomenological targets (2)

Second benchmark scenario: light scalar pair-production in 125 GeV Higgs boson decays

$$e^+e^- \to Z\,H \to Z\,S\,S$$

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 this focus topic (there is a dedicated topic focusing on LLPs).

Theoretical and phenomenological targets (2)

Second benchmark scenario: light scalar pair-production in 125 GeV Higgs boson decays

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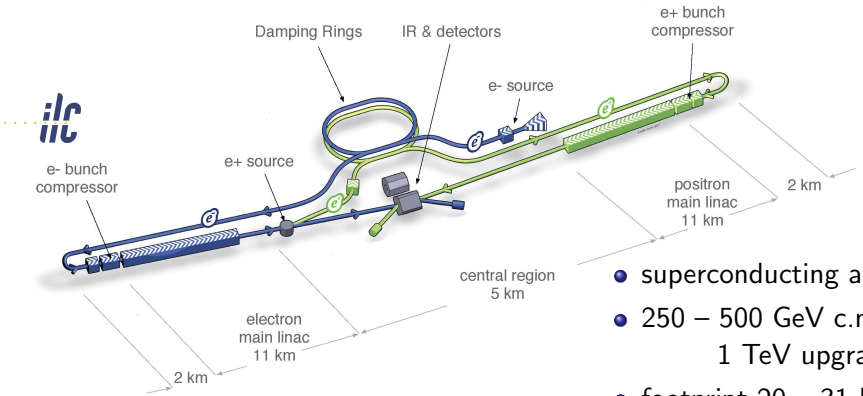
In this talk I will focus on results obtained in my group at University of Warsaw for the focus topic target (1): **direct light Higgs production in the scalar-strahlung process**
But I will also report on other results presented at the recent ECFA workshop in Paris.

Most studies were carried out in the framework of the **ILD concept group**
But the results should be quite general, applying to all 240–250 GeV e^+e^- machines...

International Linear Collider Technical Design (TDR) presented in 2013 arXiv:1306.6328



- superconducting accelerating cavities
- 250 – 500 GeV c.m.s. energy (baseline), 1 TeV upgrade possible
- footprint 20 – 31 km

- polarisation for both e^- and e^+ (80%/30%)
- staged construction, starting as 250 GeV Higgs factory arXiv:1903.01629

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

arXiv:1903.01629

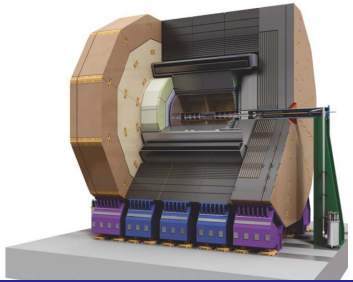
Baseline detector requirements

- Track momentum resolution: $\sigma_{1/p_t} = 2 \cdot 10^{-5}\ \text{GeV}^{-1} \oplus 1 \cdot 10^{-3}/(p_t \sin^{1/2}\Theta)$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\,\mu m\ \text{GeV}/(p \sin^{3/2}\Theta)$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (for highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

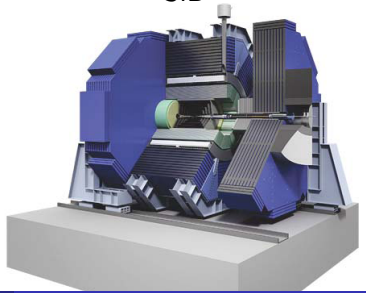
Two detailed ILC detector concepts optimized for particle flow event reconstruction

Design is constantly being improved based on new detector and software technologies

ILD



SiD



Fast simulation

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

Signal generated by varying H mass in the model and forcing its decay to considered final state.
$\tau^+\tau^-$, $b\bar{b}$ or $ZZ \to \nu\bar{\nu}\nu\bar{\nu}$

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.
Contribution from $\gamma e^{\pm}$ and $\gamma\gamma$ interactions (BS and EPA) included for invisible decays

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

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

Fast detector simulation with Delphes ILCgen model.

Full simulation

Full simulation study based on existing ILD Monte Carlo samples for SM processes at 250 GeV:

- generated with Whizard v.2.8.5,
- using default (SetA) ILC beam-spectrum,
- simulated and reconstructed using a full (GEANT 4) ILD detector simulation with ILD_l5_o2_v02 model and ILCSoft v02-02-01,
- processed using MARLIN modular framework for jet clustering and flavour tagging based on LCFIplus.

Signal samples, for scalar particle mass from 10 GeV up to 160 GeV, were generated and processed with the same tools, but for the detector simulation which was done with SGV.

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

Event categories

Focusing on hadronic decays, $Z \to q\bar{q}$ (order of magnitude higher than leptonic Z decays)
Five event categories, according to number of isolated leptons and τ-tagged jets

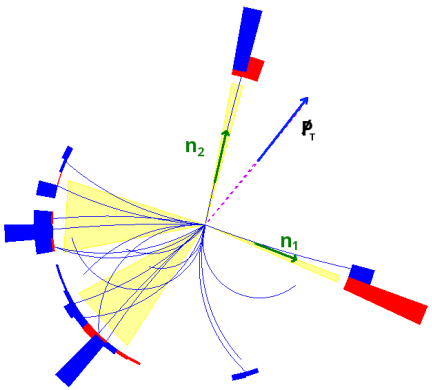
category	**isolated leptons**	**tight selection**	**loose selection**
hadronic	zero	4 jets including 2 with τ-tag	4 jets, 1 with τ-tag and other lightest jet as second τ- tag jet
semi-leptonic	one	3 jets including 1 with τ-tag	3 jets with no τ-tag, lightest jet as τ- tag jet
leptonic	two	two jets without τ-tag	

Event classification was considered separately for each category and polarization!

Event 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 !

Event reconstruction

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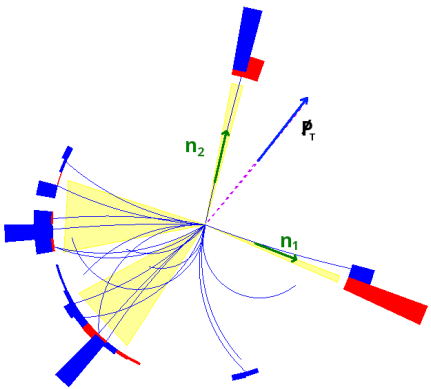

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where $\vec{n_1}$ and $\vec{n_2}$ are directions of the two tau jets.

Unique solution !

Works also for semi-leptonic and leptonic events!

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

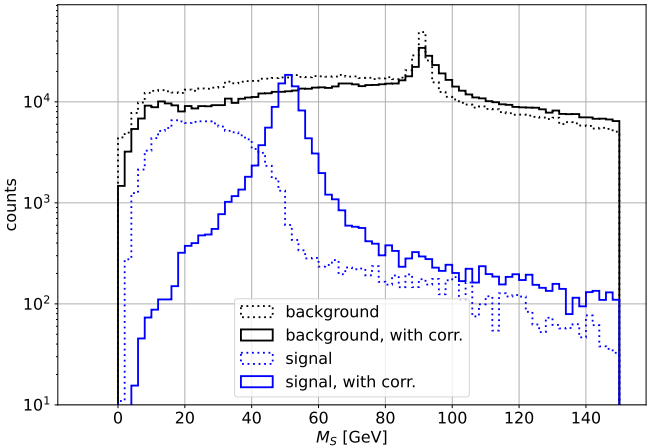
Event reconstruction

Kamil Zembaczyński (University of Warsaw)

Impact of the neutrino energy correction on the reconstructed di-tau mass distribution ⇒

Signal for scalar mass of **50 GeV**. Normalized to 1% of the SM production cross section for the considered scalar mass.

Example of $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight** selection of **semi-leptonic** events.



Event classification

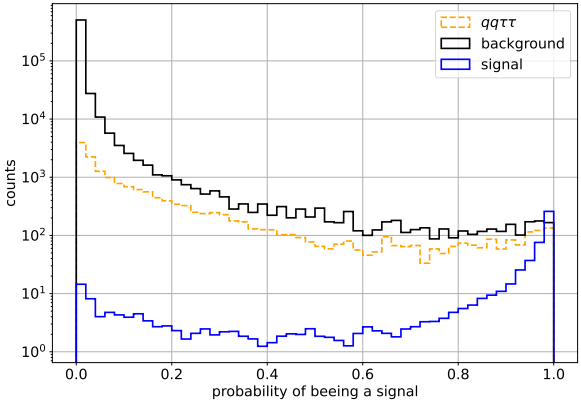
Kamil Zembaczyński (University of Warsaw)

XGBoost BDT classifier response distributions for signal and background dominant $qq\tau\tau$ background indicated

Example for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight semi-leptonic** event selection.

Signal for scalar mass of **50 GeV** normalized to 1% of SM cross section.

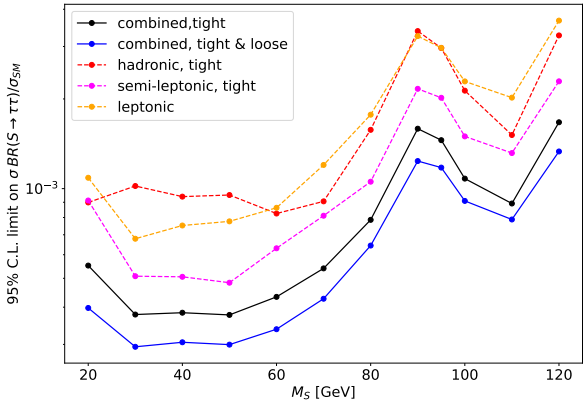
Separate BDT trained for each event class and polarization combination



Results

Kamil Zembaczyński (University of Warsaw)

Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)$
for different event categories and combined analysis



Semi-leptonic sample most sensitive to new scalar production

Significant improvement when including loose-selection categories

Marginal impact of normalization uncertainties (theory + lumi).

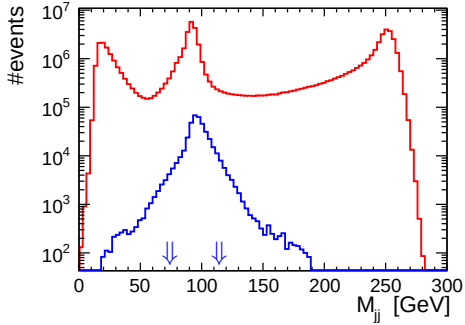
Event reconstruction

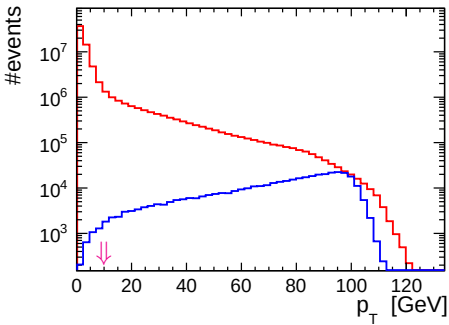
Kamil Zembaczyński (University of Warsaw)

Focusing on hadronic decays, $Z \to q\bar{q}$, require no other activity in the detector.

order of magnitude higher than leptonic Z decays

Reconstructed Z (di-jet) mass and transverse momentum for 50 GeV scalar signal and SM bg.





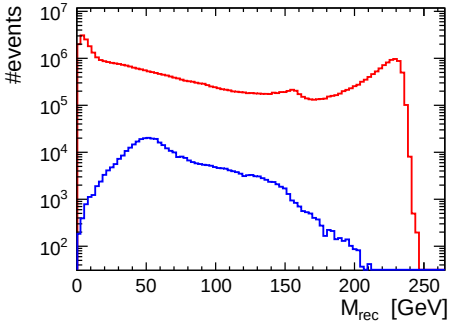
Signal normalized to 1% of SM cross section.

Event selection

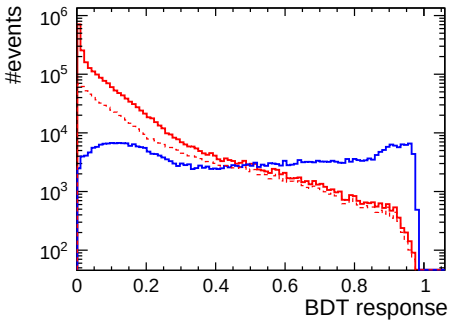
Kamil Zembaczyński (University of Warsaw)

Additional pre-selection of candidate events: $74 < M_{jj} < 114\,\text{GeV}$ and $p_T > 10\,\text{GeV}$.

Reconstructed scalar mass and BDT classifier response for 50 GeV scalar signal and SM bg.



Signal normalized to 1% of SM cross section.

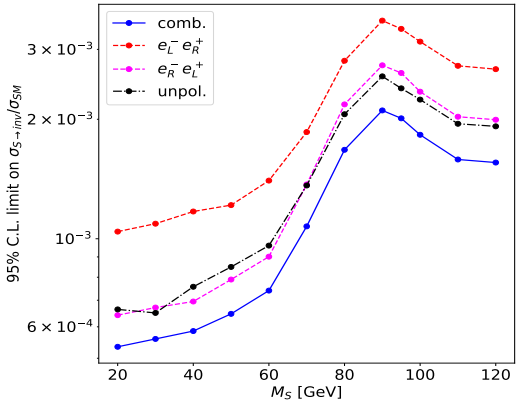


Dashed: $qq\ell\nu$ background.

Results

Kamil Zembaczyński (University of Warsaw)

Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \text{inv})$
for different polarization settings and combined analysis



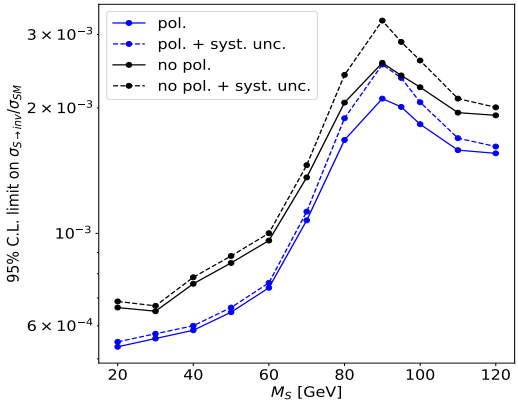
Highest sensitivity in $e_R^- e_L^+$ mode: suppressed W^+W^- background

Polarisation results in about 20% improvement in the sensitivity.

Results

Kamil Zembaczyński (University of Warsaw)

Cross section limits for $\sigma(e^+e^- \rightarrow Z\,S) \cdot BR(S \rightarrow \text{inv})$
for H-20 scenario and unpolarized running with the same luminosity



Visible impact of systematic uncertainties

theory predictions: 0.2% for e^+e^-
1% for $\gamma e^{\pm}$ and $\gamma\gamma$

sample normalization: 0.2% for LR and RL
0.5% for LL and RR

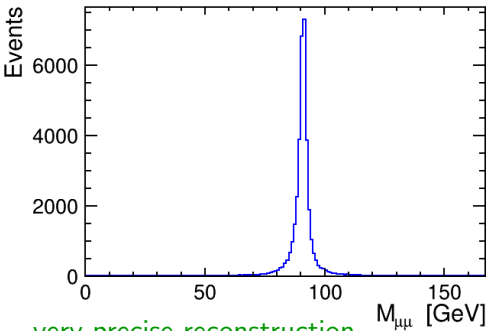
Significant impact for $M_S \sim M_Z$

Event reconstruction

Bartłomiej Brudnowski (University of Warsaw)

Focusing on leptonic decays, $Z \to e^+e^-/\mu^+\mu^-$; huge W^+W^- background for hadronic decays

Z mass from leptonic decays:



very precise reconstruction...

Direct reconstruction of the scalar mass much more problematic. Invariant mass of two b jets poorly reconstructed, large impact of energy losses in semi-leptonic heavy meson decays.

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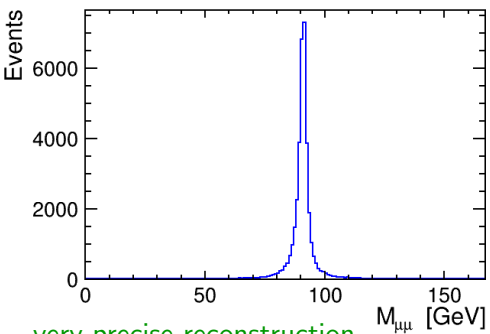


very precise reconstruction...

Direct reconstruction of the scalar mass much more problematic. Invariant mass of two b jets poorly reconstructed, large impact of energy losses in semi-leptonic heavy meson decays.

However, conservation of transverse momentum can be used to reconstruct jet energies from leptonic final state and jet angles.

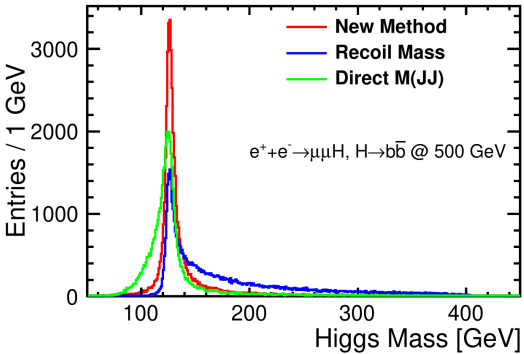
ILD-PHYS-PUB-2019-001

Event reconstruction

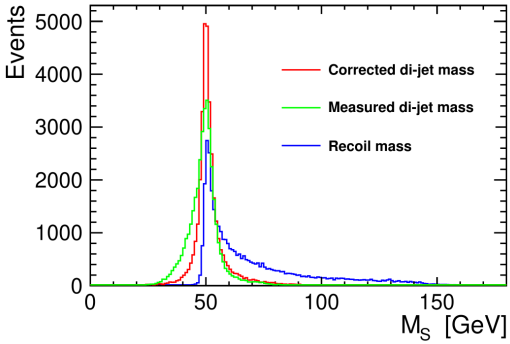
Bartłomiej Brudnowski (University of Warsaw)

Focusing on leptonic decays, $Z \to e^+e^-/\mu^+\mu^-$; huge W^+W^- background for hadronic decays

Full simulation for H_{125} at 500 GeV



Fast simulation for 50 GeV scalar at 250 GeV



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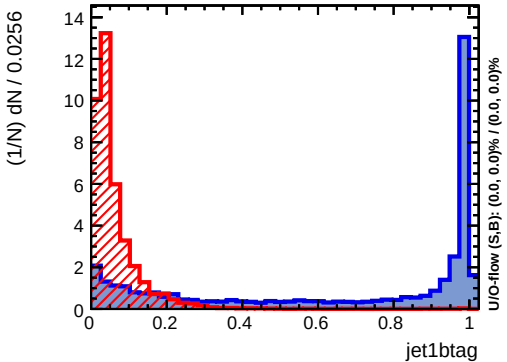
Flavour tagging

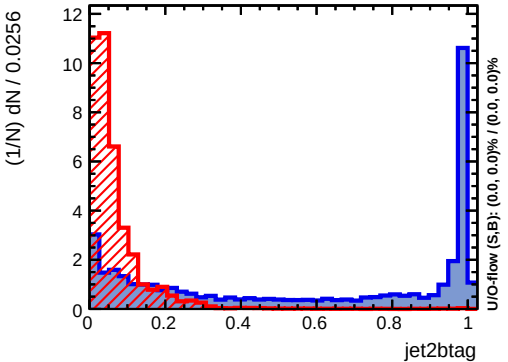
Bartłomiej Brudnowski (University of Warsaw)
supervised by María Teresa Núñez Pardo de Vera (DESY)

Tagging of b jets crucial for background suppression.

Use SM background full simulation samples for more reliable estimate of selection efficiency.

Clear separation of signal events from (mostly light flavour) SM backgrounds





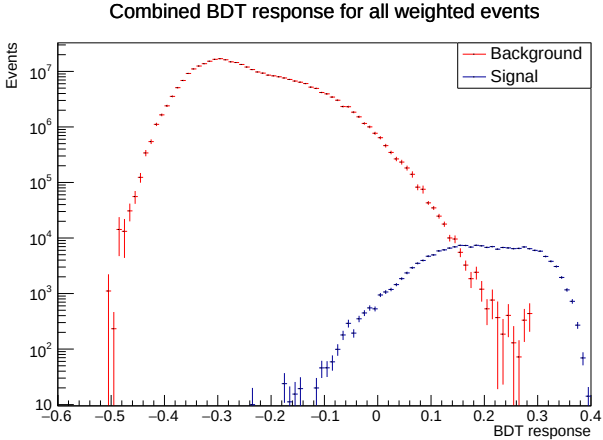
Event classification

Bartłomiej Brudnowski (University of Warsaw)
supervised by María Teresa Núñez Pardo de Vera (DESY)

Results from the BDT classifier used on the preselected event samples (two electrons or muons, two b-tagged jets)

Example for scalar mass $M_S = 50\,\text{GeV}$ scenario normalized to 1% of the $\sigma_{SM}(M_S)$

Full simulation



Results

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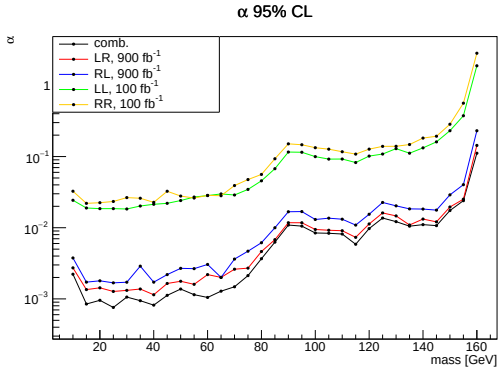
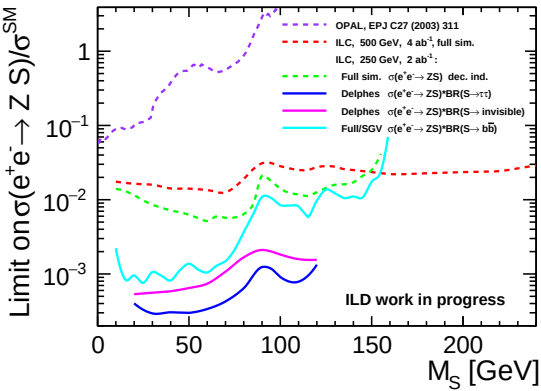
Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to b\bar{b})$
for different polarization settings and combined analysis



Little impact of the beam polarisation
Background dominated by ZZ production

Comparison of recent results

Cross section limits for $\sigma(e^+e^- \to Z\,S)$ times branching ratio in the considered channel compared with previous decay independent study

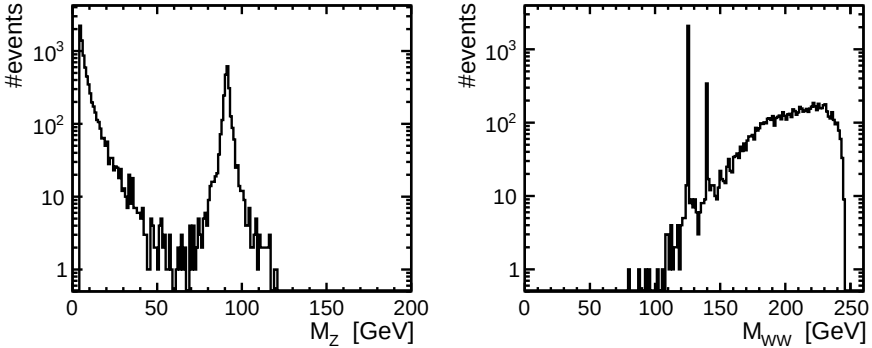


Order of magnitude improvement in the low mass domain, compared to the decay independent search.

$b\bar{b}$ limited by statistics of leptonic Z decays...

Ongoing study with Tania Robens, Yang Ma, Mohamed Ouchemhou

Whizard simulation of $e^+e^- \to \mu^+\mu^- \, q\,\bar{q}' \, e\,\nu_e$ (6 fermion final state, no restrictions)
Should correspond to $Z\,W^+W^-$ for the expected signal



TRSM model with additional 140 GeV scalar at $\sqrt{s}$ =250 GeV

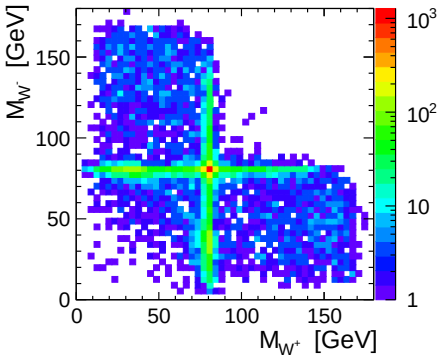
Ongoing study

with Tania Robens, Yang Ma, Mohamed Ouchemhou

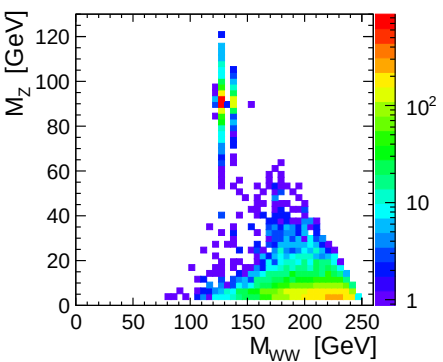
Correlation of reconstructed boson masses on generator level

TRSM model with additional 140 GeV scalar at $\sqrt{s}$ =250 GeV

All events



Clear separation of scalar production



Ongoing study

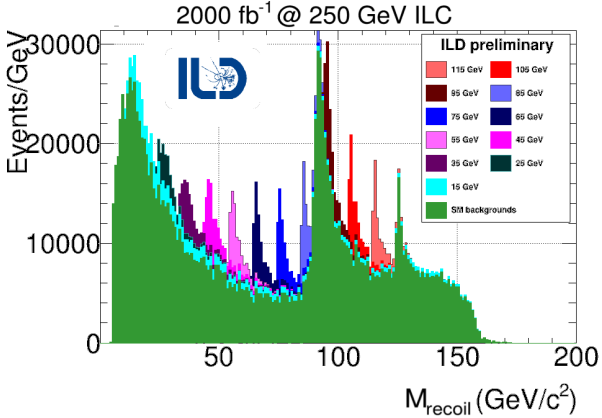
presented by María Teresa Núñez Pardo de Vera

Follow the approach used in the SM-like Higgs boson analysis in the ZH production channel: use "Z-tagging" with $Z \to e^+e^-/\mu^+\mu^-$ for unbiased selection of scalar production events.

Search strategy based on the reconstructed recoil mass spectra

Previous full simulation study:

arXiv:1903.01629 arXiv:2005.06265 $\Rightarrow$

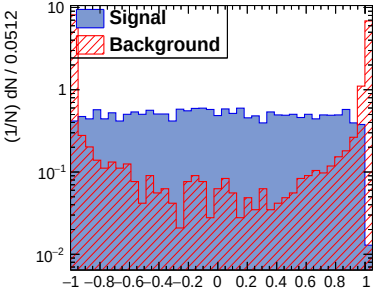


Ongoing study

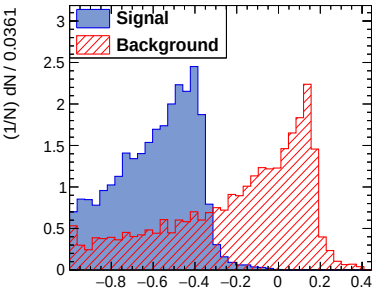
presented by María Teresa Núñez Pardo de Vera

Limits likely to improve with use of up-to-date simulation, reconstruction and analysis tools.
Ongoing full simulation study, results being prepared for the ECFA report

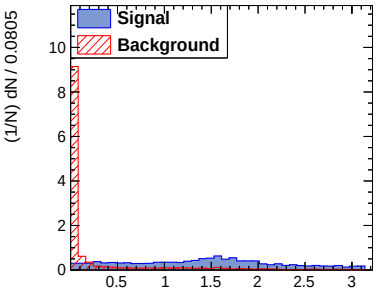
Example results: variables describing di-muon final state from Z decay



$\cos\theta_Z$



$\cos\angle^{\mu}_{\mu}$



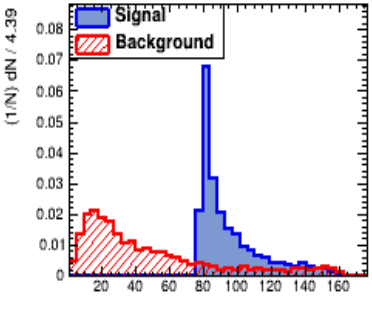
Acoplanarity

Ongoing study

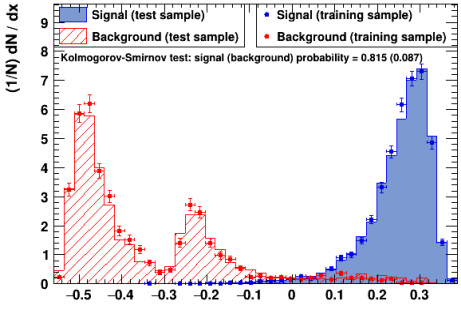
presented by María Teresa Núñez Pardo de Vera

Limits likely to improve with use of up-to-date simulation, reconstruction and analysis tools.
Ongoing full simulation study, results being prepared for the ECFA report

Example results: discrimination between 2f background and ZS production (80 GeV scalar).



Recoil mass [GeV]



BDT response

Light pseudo-scalar production in Higgs boson decays at C^3

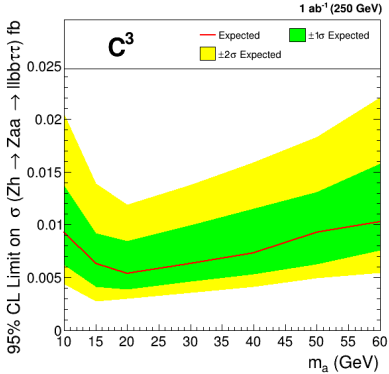
presented by Cheng-Hsu (Bryan) Nee

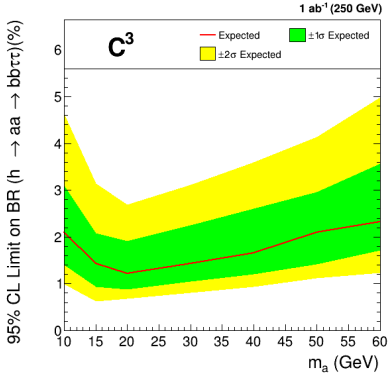
Search for a pair of light (20-60 GeV) scalars from SM Higgs decay.
Higgs produced in association with a Z boson at 250 GeV:

$$e^+e^- \to Z\,H \;\to\; Z\,a\,a \to (e^+e^-/\mu^+\mu^-)\;\;(b\,\bar{b})\;\;(\tau^+\tau^-)$$

Model-independent limits:

The limit is much more sensitive in the lower mass region than the CMS Run 2 result.



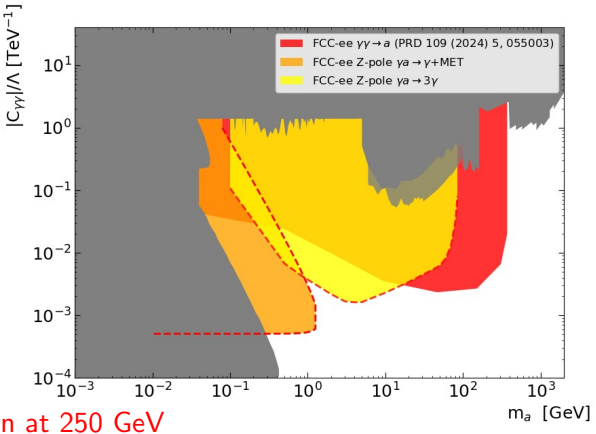


Z-pole searches for ALPs at FCC-ee

presented by Giacomo Polesello

IDEA fast simulation study
Assume BR($a \to \gamma\gamma$)=100%
$\Rightarrow$ three photon signature
(or photon + MET)

Both prompt decays and long-lived ALP scenarios considered.



Grey areas: exclusions taken from ATLAS

Red area: production in photon-photon fusion at 250 GeV

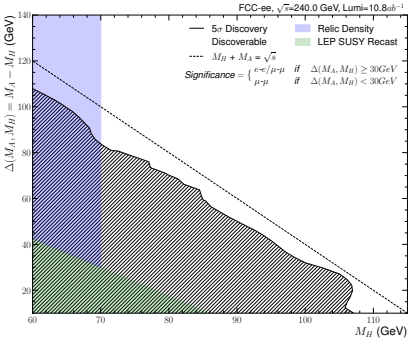
Search for additional Higgs bosons at the FCC-ee

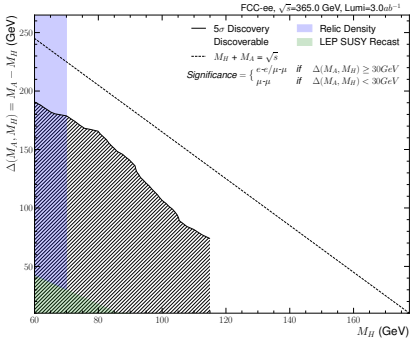
presented by Anne-Marie Magnan

Pair production within the Inert Doublet Model, final state with two electrons or two muons.

Discovery prospects at 240 GeV and 365 GeV

Good agreement with earlier CLIC and ILC studies
arXiv:1811.06952
arXiv:2002.11716





Conclusions

BSM scenarios with light exotic scalars still not excluded by existing data

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

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12 contributions presented at the recent ECFA workshop in Paris!
Final ECFA report, with an extended section on light exotic scalar searches, will be submitted as an input to the European Strategy Update in March 2025.

Thank you!