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

Aleksander Filip Żarnecki

Faculty of Physics, University of Warsaw

Corfu2024

Workshop on the Standard Model and Beyond

August 25 - September 4, 2024

Prospects for light exotic scalar measurements

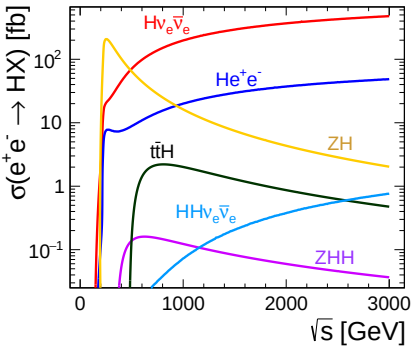
Outline:

1. Motivation
2. ILC and its experiments
3. Light exotic scalar searches
   - Decay mode independent
   - $S \to \tau^+\tau^-$
   - $S \to b\bar{b}$
   - $S \to$ invisible
   - $S \to W^+W^-$
4. Conclusions

This is a collaborative effort, mine are only few of the results, but all omissions and mistakes...

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.

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...

e^+e^- Higgs factory

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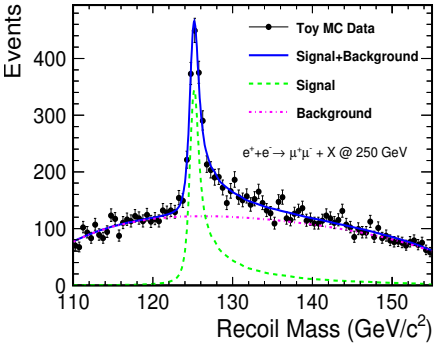
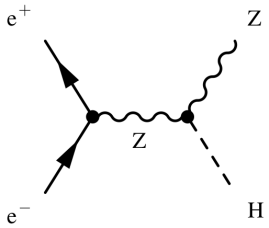


At 250 GeV we will focus on H_{125} production



e^+e^- Higgs factory

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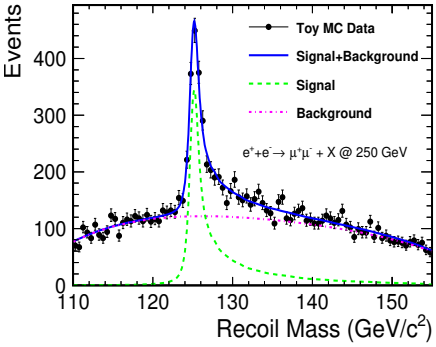

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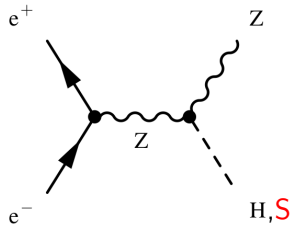
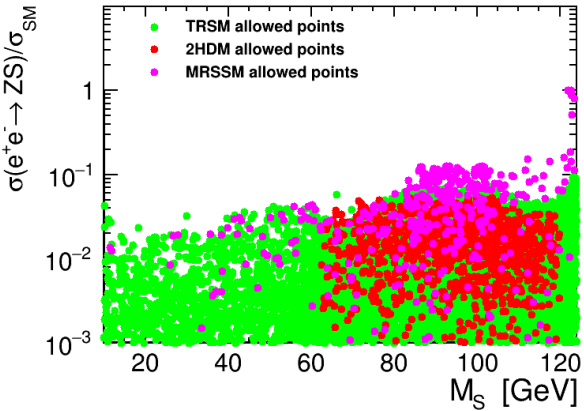


But production of additional, light exotic scalar states is still not excluded by the existing data!

Possible scenarios (as 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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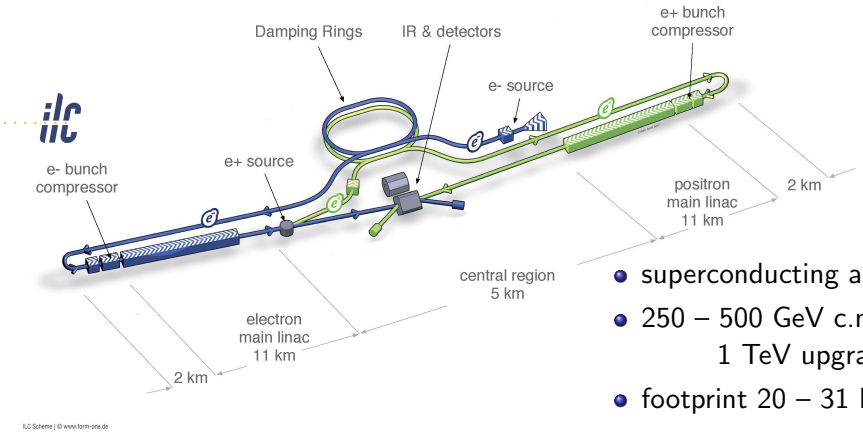
In this talk I will focus on the new activities triggered by the ECFA study on EXscalar focus topic target (1): **direct light Higgs production in the scalar-strahlung process**

Presented 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

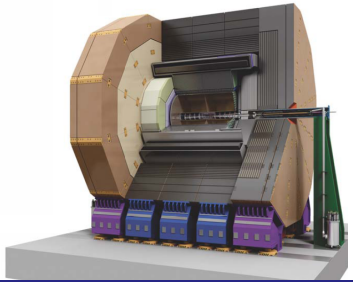
Baseline detector requirements

- 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

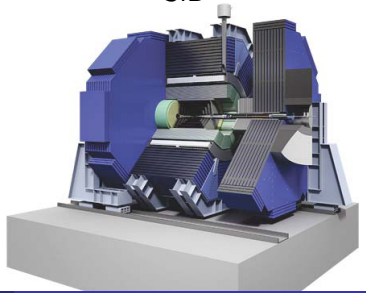
Two detailed ILC detector concepts optimized for particle flow event reconstruction

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

ILD

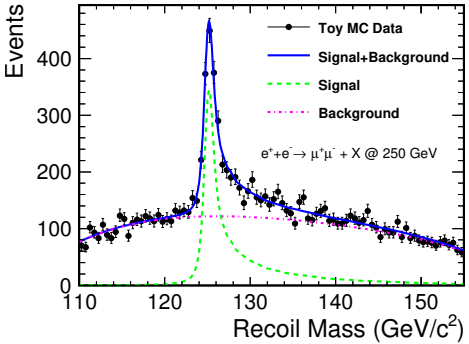


SiD



Event reconstruction

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

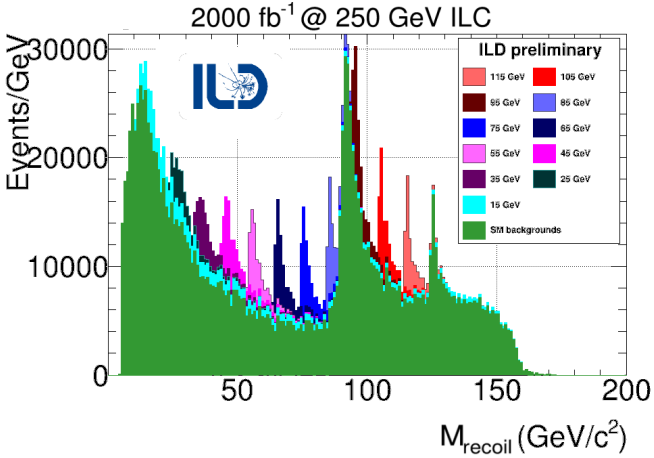


We avoid any possible dependence on the scalar decay channels (could be exotic or invisible)!

Decay mode independent search

Analysis

arXiv:1903.01629 arXiv:2005.06265



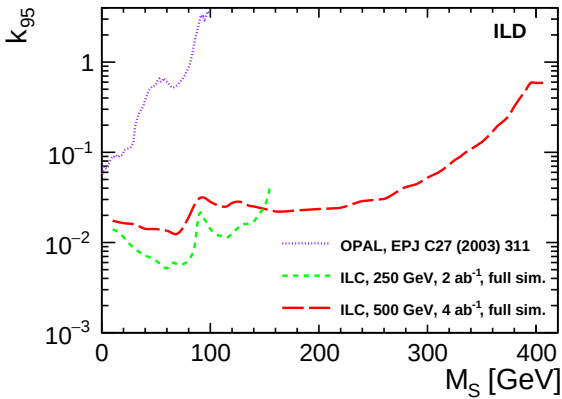
ILD full simulation study for

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

Search strategy based on the reconstructed recoil mass spectra

Results

arXiv:1903.01629 arXiv:2005.06265



Scalar search sensitivity
for ILC @ 250 GeV and 500 GeV

expected 95% C.L. limits on the cross section ratio

$$k = \frac{\sigma\left(e^+e^- \to Z\,S\right)}{\sigma^{SM}\left(e^+e^- \to Z\,H\right)|_{m_H=m_S}}$$

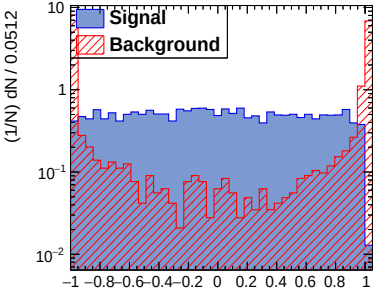
scalar production cross section relative to SM Higgs boson production cross section at given mass

Prospects

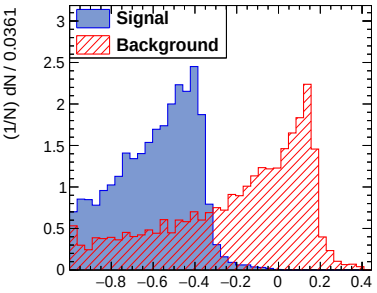
María Teresa Núñez Pardo de Vera (DESY)

Limits likely to improve with use of up-to-date simulation, reconstruction and analysis tools.
Ongoing full simulation study, results expected for ECFA workshop in Paris (in October)

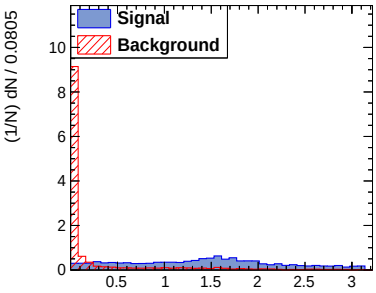
Example results: variables describing di-muon final state from Z decay



$\cos\theta_Z$



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



Acoplanarity

Prospects

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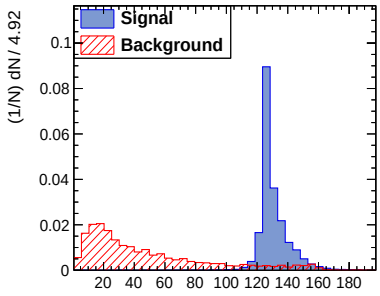
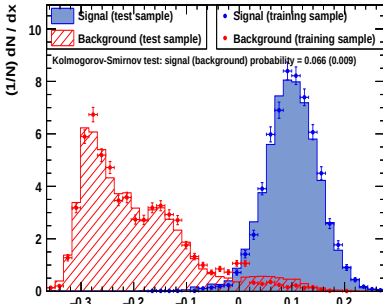
Example results: discrimination between 2f background and ZH production.



Recoil mass [GeV]



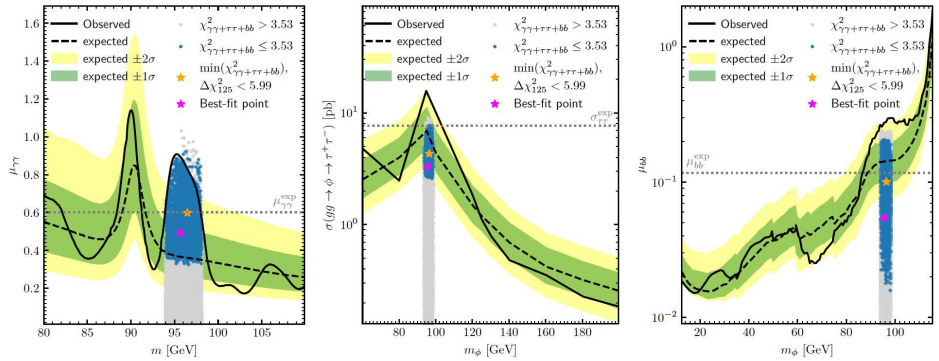
BDT response

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 $\tau\tau$...

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



Sven Heinemeyer @ First ECFA WS, October 2022

Analysis framework

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 $\tau^+\tau^-$

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 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.

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

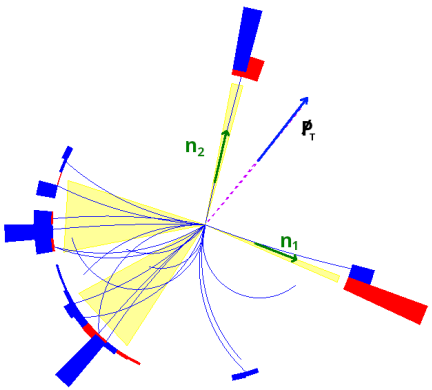
category	**isolated leptons**	**tight selection**	**loose selection**
hadronic	zero	4 jets including 2 with τ-tag	4 jets, 1 with τ-tag and other lightest jet as second τ- tag jet
semi-leptonic	one	3 jets including 1 with τ-tag	3 jets with no τ-tag, lightest jet as τ- tag jet
leptonic	two	two jets without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

arXiv:1509.01885

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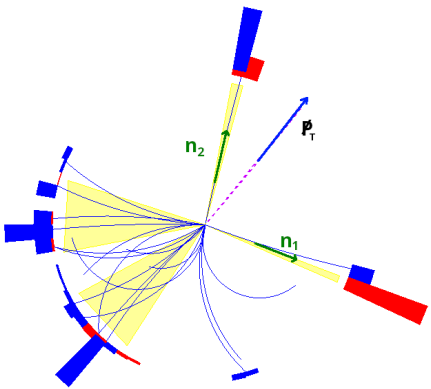

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where $\vec{n_1}$ and $\vec{n_2}$ are directions of the two tau jets.

Unique solution !

Works also for semi-leptonic and leptonic events!

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

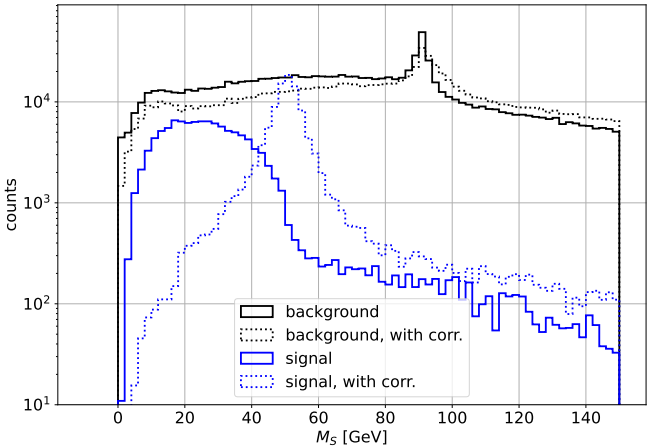
Event reconstruction

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.

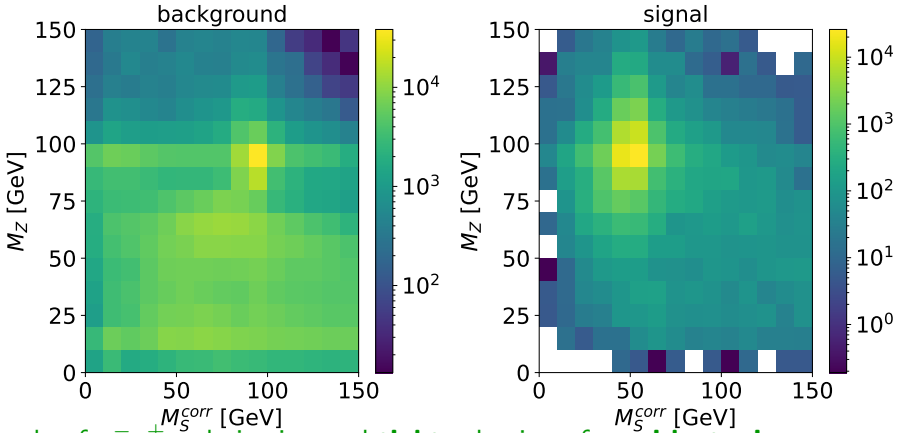
Example of $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight** selection of **semi-leptonic** events.



Event reconstruction

Kamil Zembaczyński (University of Warsaw)

Corrected scalar mass vs reconstructed Z mass for 50 GeV scalar and SM background



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

Event classification

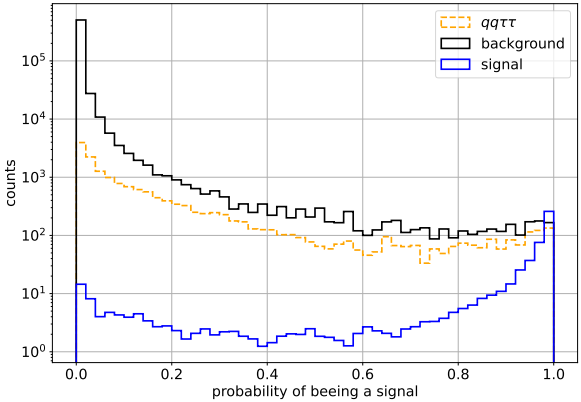
Kamil Zembaczyński (University of Warsaw)

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.

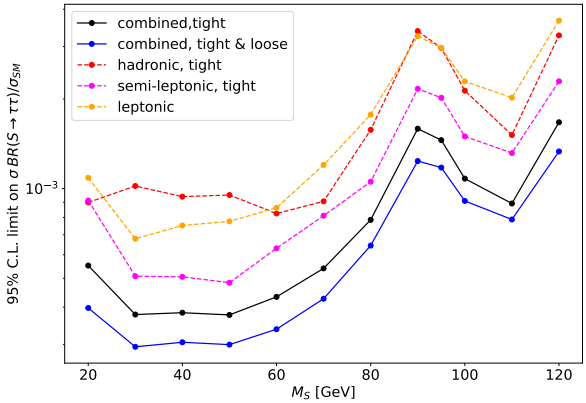
Separate BDT trained for each event class and polarization combination



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



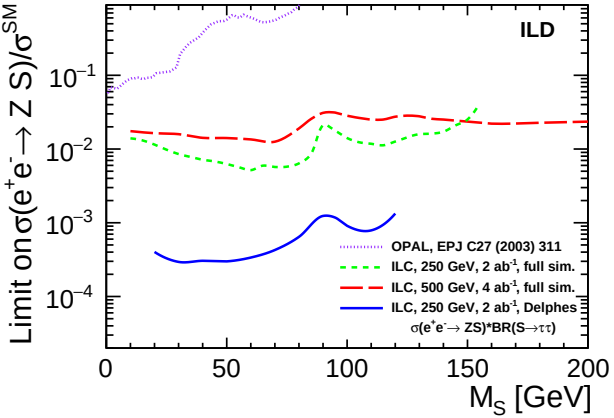
Semi-leptonic sample most sensitive to new scalar production

Significant improvement when including loose-selection categories

Results

Kamil Zembaczyński (University of Warsaw)

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



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

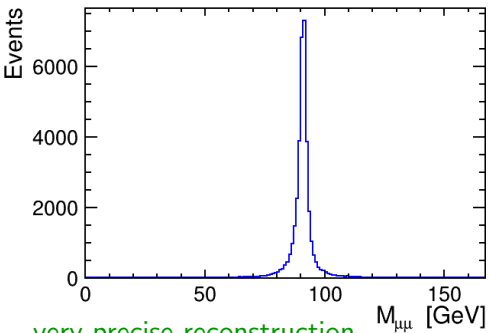
Possible gain in discovery reach depends on the BR!

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.

Event reconstruction

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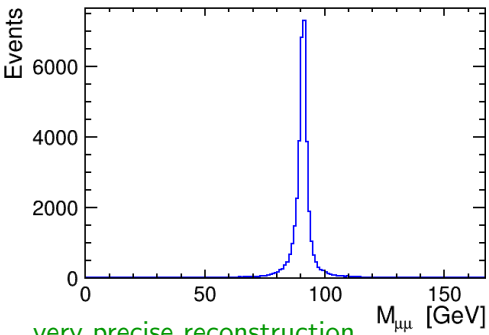


very precise reconstruction...

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.

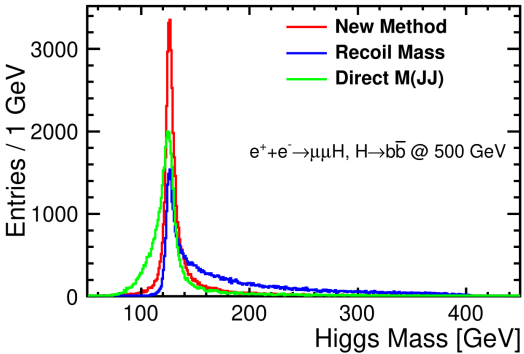
ILD-PHYS-PUB-2019-001

Event reconstruction

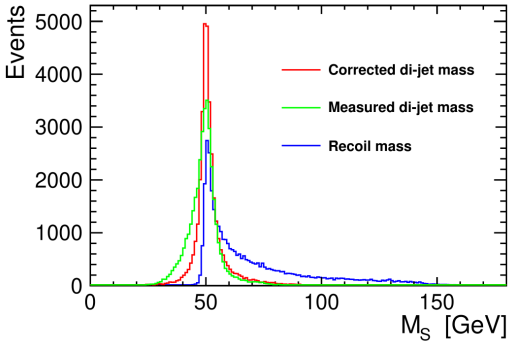
Bartłomiej Brudnowski (University of Warsaw)

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



ILD-PHYS-PUB-2019-001

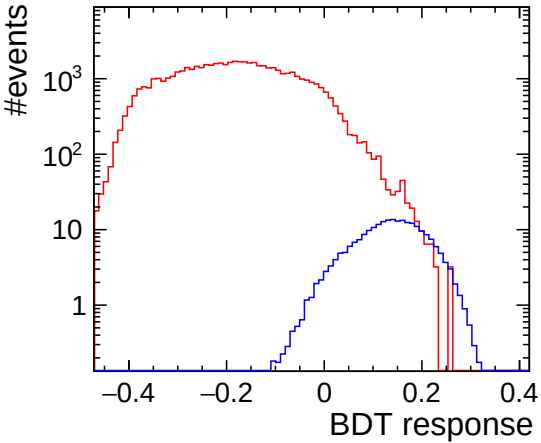
Event classification

Bartłomiej Brudnowski (University of Warsaw)

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

Example for $e_R^- e_L^+$ polarization, scalar mass $M_S = 80\,\text{GeV}$ scenario normalized to 1% of the $\sigma_{SM}(M_S)$

Full simulation study in progress...

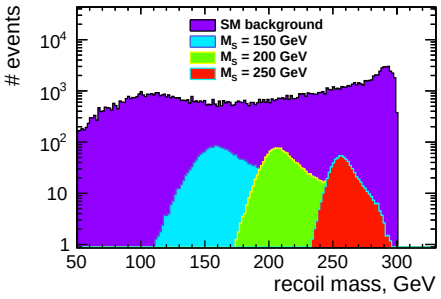


CLIC study

Previously only studied for CLIC @ 380 GeV

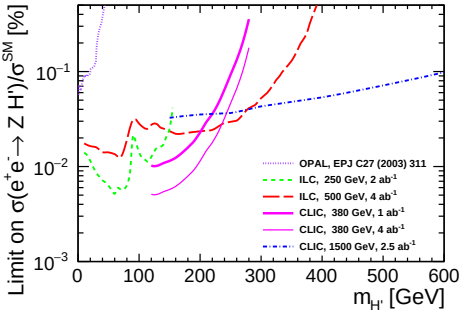
arXiv:2002.06034 arXiv:2107.13903

Reconstructed recoil mass spectra



hadronic Z decays for maximum sensitivity

Expected sensitivities of CLIC @ 380 GeV and 1.5 TeV



compared with decay independent limits from LEP and ILC

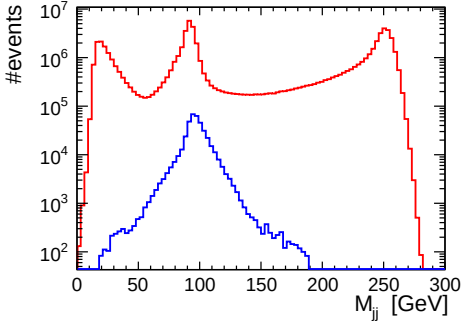
Event reconstruction

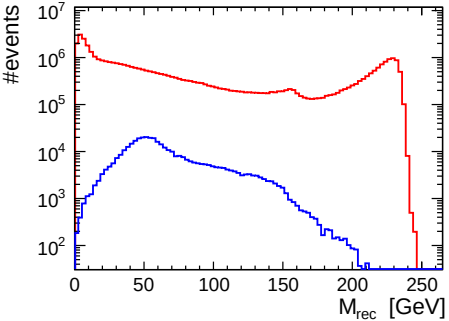
Kamil Zembaczyński (University of Warsaw)

using same analysis framework and background samples as for $S \rightarrow \tau^+\tau^-$

Focusing on hadronic decays, $Z \rightarrow q\bar{q}$: order of magnitude higher than leptonic Z decays

Reconstructed Z (di-jet) and scalar (recoil) masses for signal of 50 GeV scalar and SM bg.





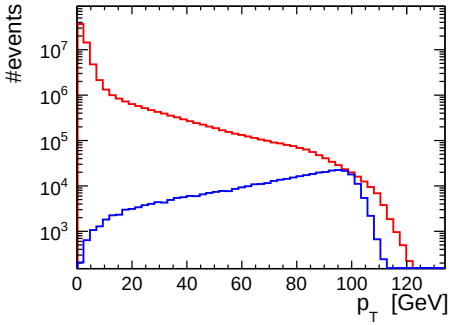
Event reconstruction

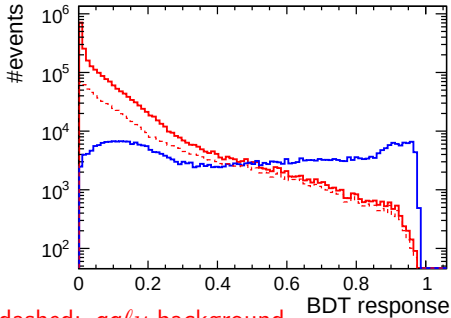
Kamil Zembaczyński (University of Warsaw)

using same analysis framework and background samples as for $S \to \tau^+\tau^-$

Focusing on hadronic decays, $Z \to q\bar{q}$: order of magnitude higher than leptonic Z decays

Z (di-jet) transverse momentum and BDT classifier response for 50 GeV scalar and SM bg.





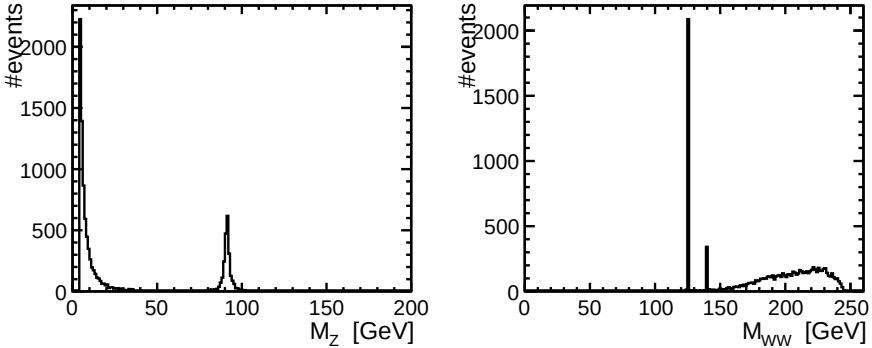
dashed: $qq\ell\nu$ background

Simulation 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

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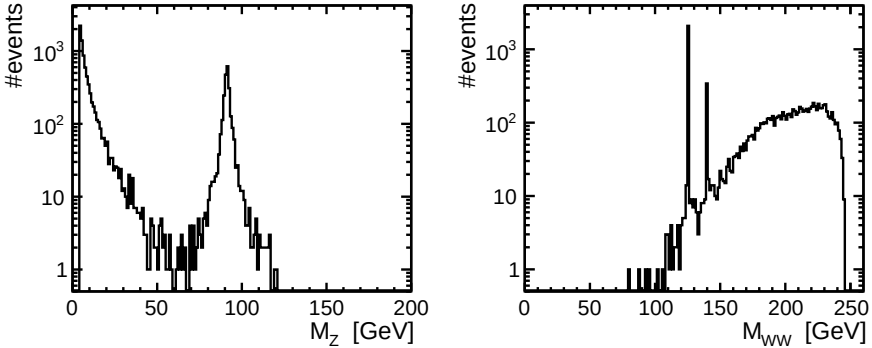

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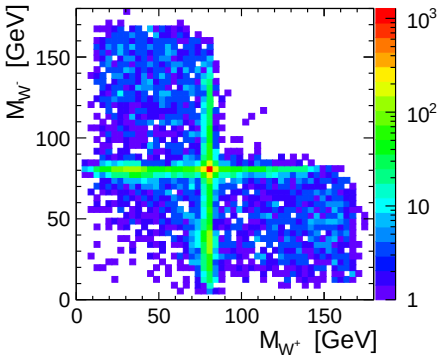
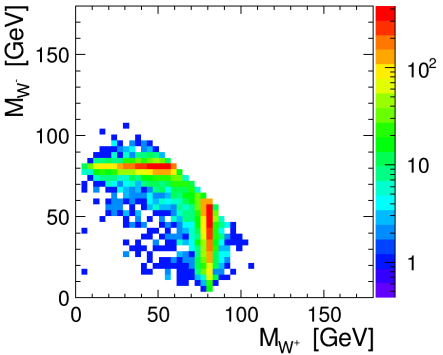
All events



140 GeV scalar only



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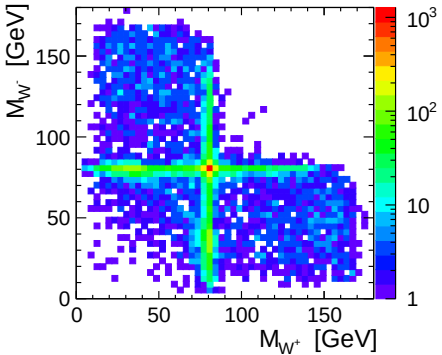
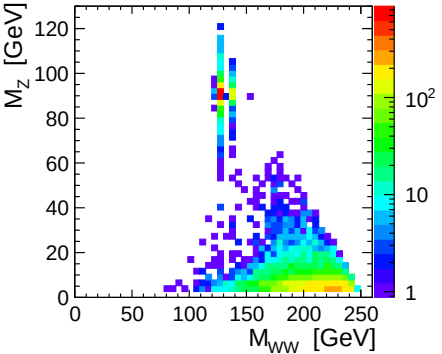


Clear separation of scalar production



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BSM scenarios with light scalars still not excluded by existing data

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Results for the ECFA study report need to be completed very soon!
Most results should be available already for ECFA workshop in October...

Thank you!

New developments

Most results are based on the ILD baseline design and corresponding simulation models.
However, both detector design and software tools are evolving.

New detector options considered for improved particle identification:

- pixel readout for the TPC $\Rightarrow$ higher reconstruction precision and cluster counting
- high precision time-of-flight counters
- additional Cherenkov counters

New reconstruction tools:

- jet clustering based on supervised learning
- flavour tagging with ML (ParticleNet)
- comprehensive partricle identification framework

Significant improvement expected for many precision measurements
(eg. Higgs self-coupling, $H \to s\bar{s}$), but also for BSM searches.