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

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Prospects for light exotic scalar measurements

Outline:

1. Introduction
2. Analysis framework
3. Light exotic scalar searches
   - $S \to \tau^+\tau^-$
   - $S \to$ invisible
   - $S \to b\bar{b}$
4. Conclusions

Most results presented are preliminary or work in progress...

EXscalar - new exotic scalars

arXiv:2401.07564

Light scalar searches at future Higgs Factories were only partially studied in the past.
To trigger new activities, understand the experimental challenges and prospects, they were selected as one of the focus topics, with two theoretical and phenomenological targets.

Target I 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.

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

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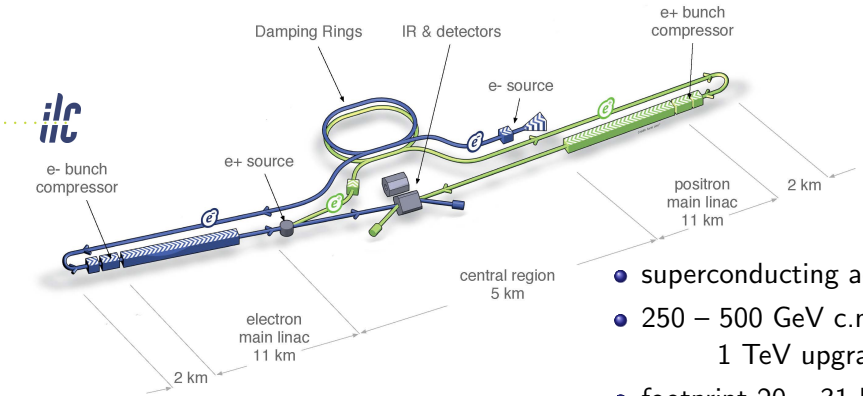
Non-standard decays channels of the new scalar can also be looked for.

In this talk I will present results obtained within this focus topic at University of Warsaw.
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

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.

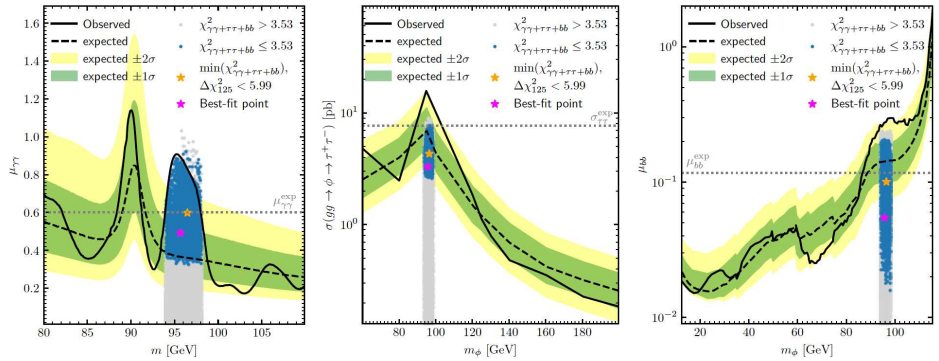
Total luminosity of $2\,\mathrm{ab}^{-1}$, with $\pm 80\%/\pm 30\%$ polarisation for e^-/e^+. (H-20 scenario)

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

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

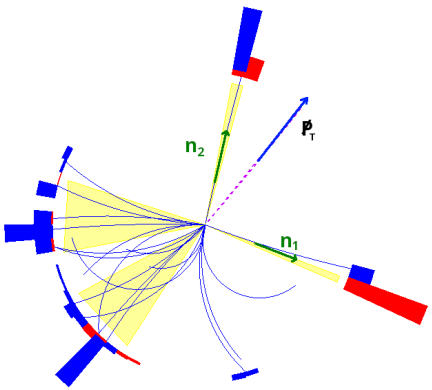
category	**isolated leptons**	**tight selection**	**loose selection**
hadronic	zero	4 jets including 2 with τ-tag	4 jets, 1 with τ-tag and other lightest jet as second τ- tag jet
semi-leptonic	one	3 jets including 1 with τ-tag	3 jets with no τ-tag, lightest jet as τ- tag jet
leptonic	two	two jets without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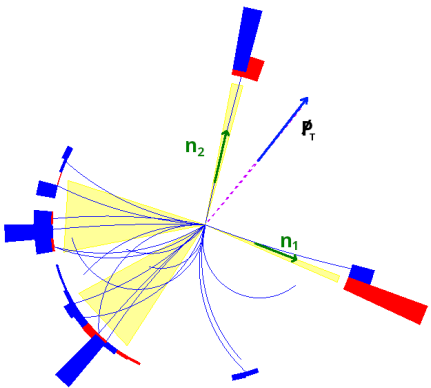

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where $\vec{n_1}$ and $\vec{n_2}$ are directions of the two tau jets.

Unique solution !

Works also for semi-leptonic and leptonic events!

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

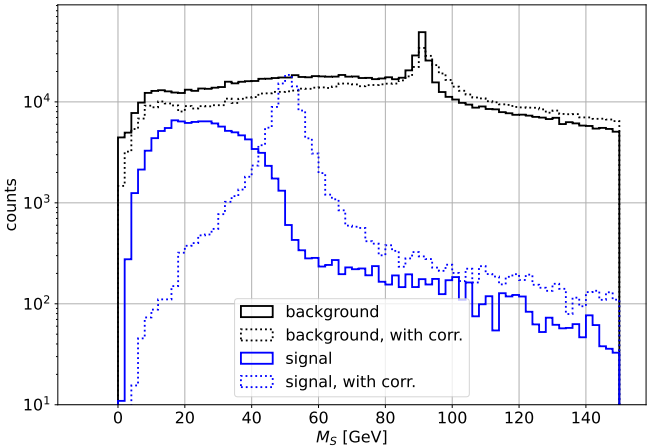
Event reconstruction

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

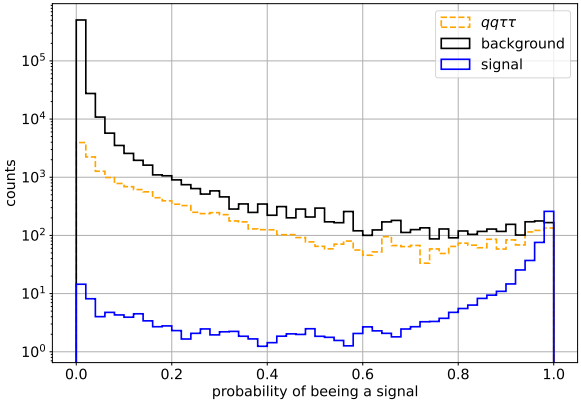
Kamil Zembaczyński (University of Warsaw)

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.

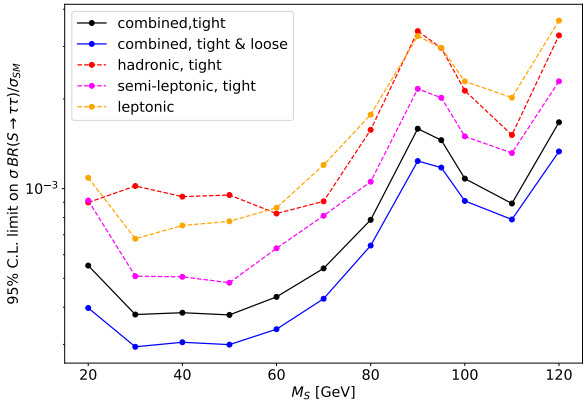
Separate BDT trained for each event class and polarization combination



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

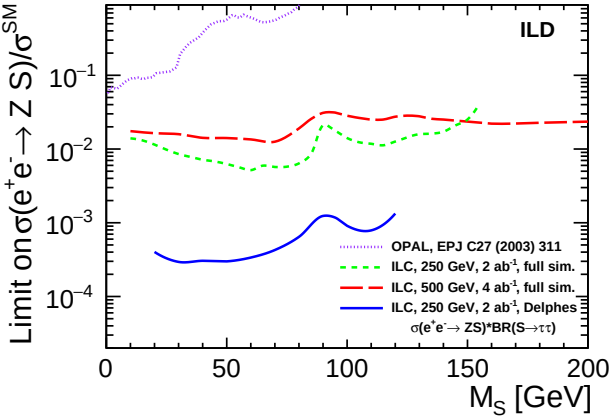
Significant improvement when including loose-selection categories

Marginal impact of normalization uncertainties (theory + lumi).

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...

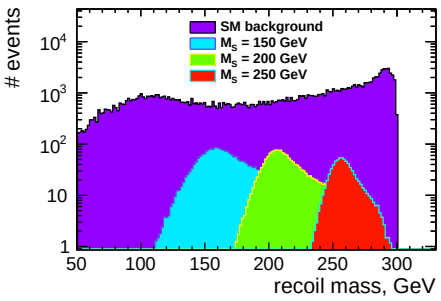
Possible gain in discovery reach depends on the BR!

CLIC study

Previously only studied for CLIC @ 380 GeV

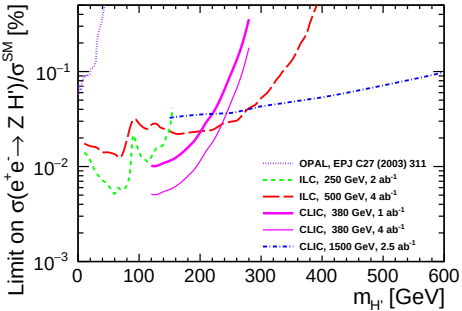
arXiv:2002.06034 arXiv:2107.13903

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

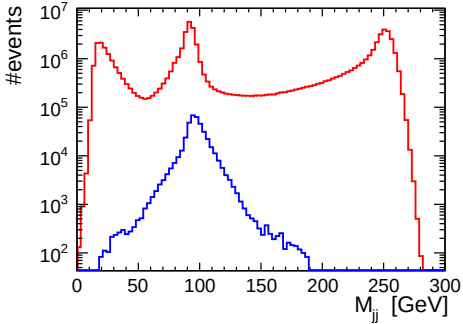
Event reconstruction

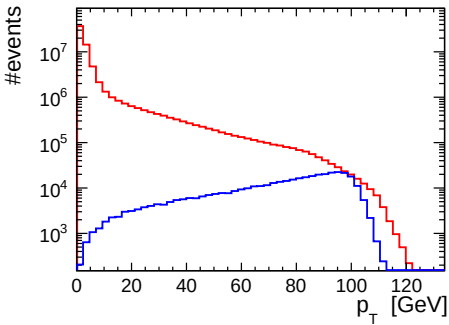
Kamil Zembaczyński (University of Warsaw)

Focusing on hadronic decays, $Z \rightarrow q\bar{q}$, 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.





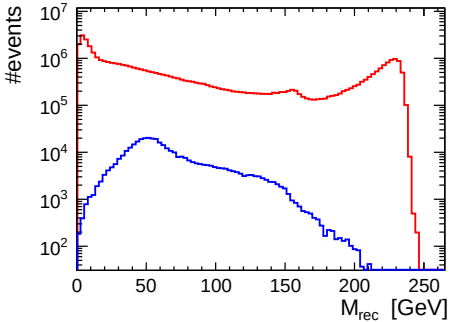
Signal normalized to 1% of SM cross section.

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.



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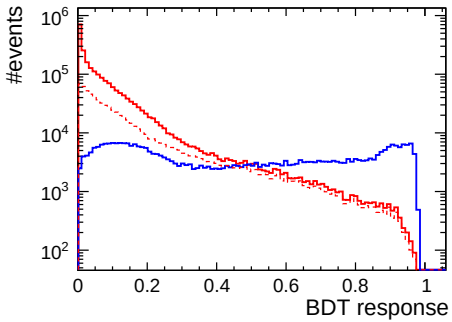

Dashed: $qq\ell\nu$ background.

Results

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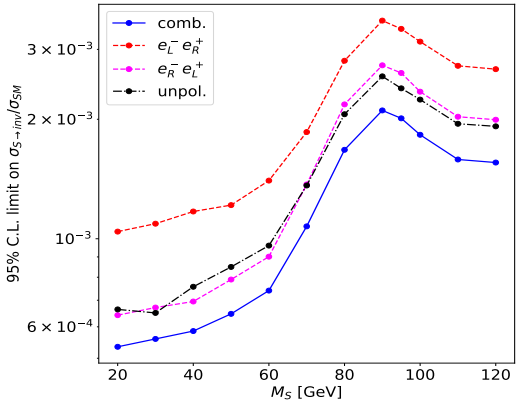
Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \text{inv})$
for different polarization settings and combined analysis



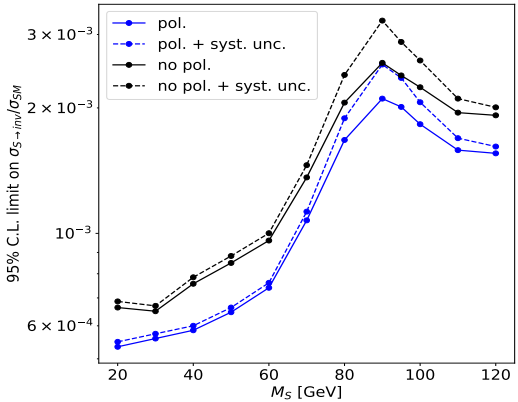
Highest sensitivity in $e_R^- e_L^+$ mode:
suppressed W^+W^- background

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 $\gamma\gamma$

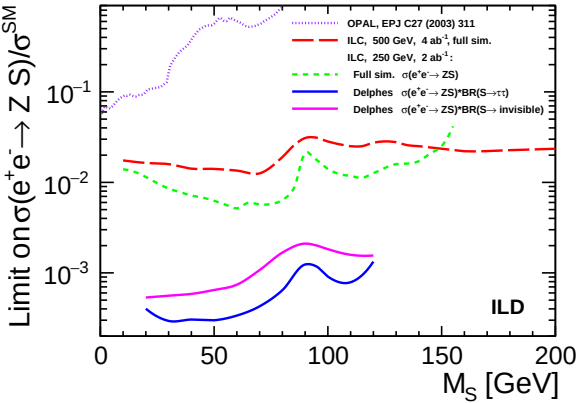
sample normalization: 0.2% for LR and RL
0.5% for LL and RR

Significant impact for $M_S \sim M_Z$

Results

Kamil Zembaczyński (University of Warsaw)

Cross section limits for $\sigma(e^+e^- \rightarrow Z\,S) \cdot BR(S \rightarrow \text{inv})$
compared with previously presented results



Sensitivity decrease by about a factor of 2, compared to the visible decay channel

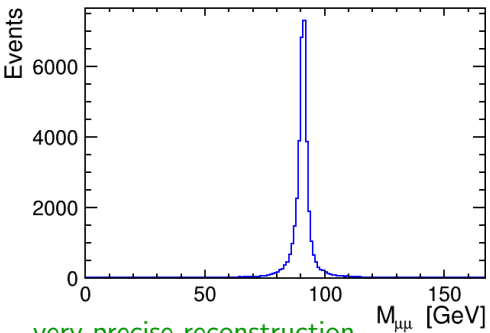
Both studies consider $Z \rightarrow q\bar{q}$

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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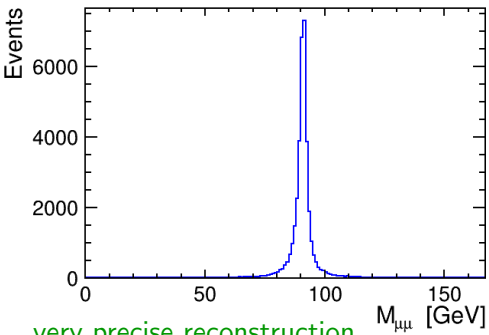

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Direct reconstruction of the scalar mass much more problematic. Invariant mass of two b jets poorly reconstructed, large impact of energy losses in semi-leptonic heavy meson decays.

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

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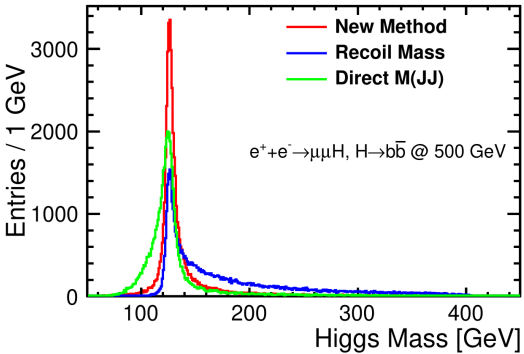
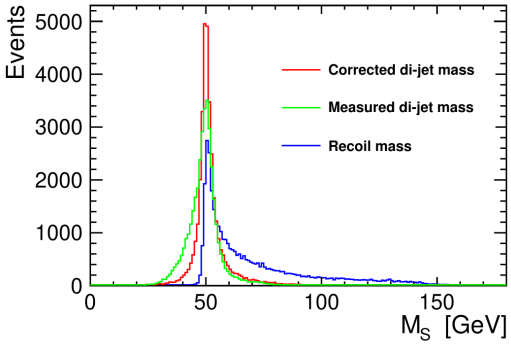
Full simulation for H_{125} at 500 GeV



Fast simulation for 50 GeV scalar at 250 GeV



ILD-PHYS-PUB-2019-001

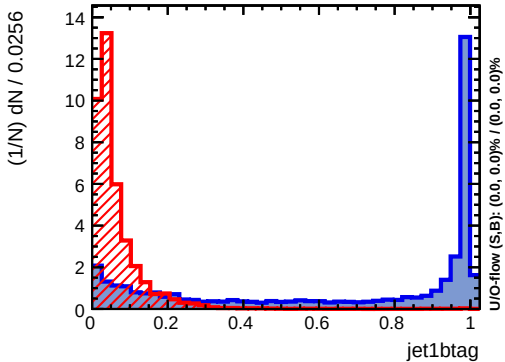
Flavour tagging

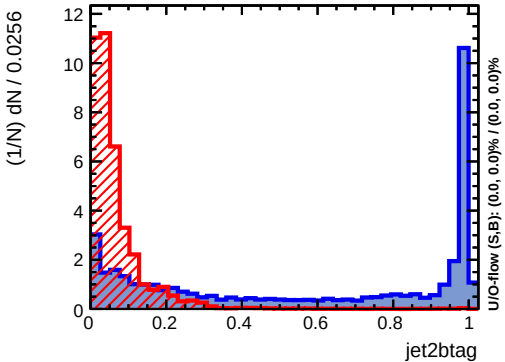
Bartłomiej Brudnowski (University of Warsaw)
supervised by María Teresa Núñez Pardo de Vera (DESY)

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





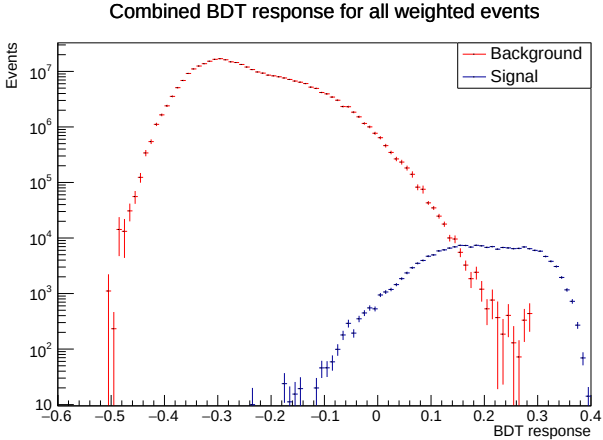
Event classification

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



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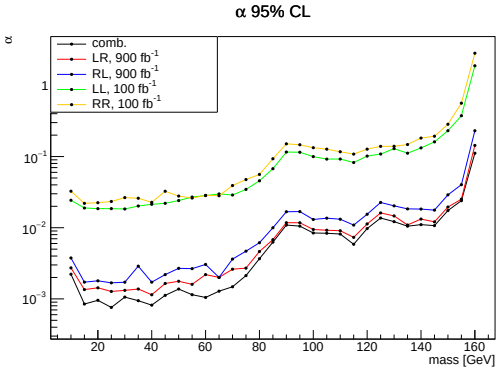

Little impact of the beam polarisation
Background dominated by ZZ production

Results

Bartłomiej Brudnowski (University of Warsaw)
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Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to b\bar{b})$
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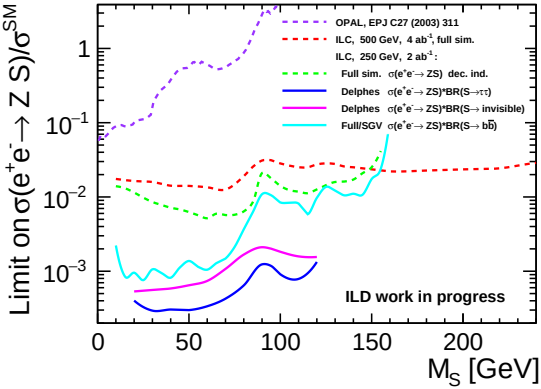

Order of magnitude improvement in the low mass domain, compared to decay independent search.

Limited by statistics of leptonic Z decays...

Conclusions

BSM scenarios with light scalars still not excluded by existing data

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

One of the focus topics of the ECFA study

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Three final states considered in the fast simulation studies at University of Warsaw.

Full simulation study for channel expected to be dominant (in many models): $S \to b\bar{b}$

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Full simulation study for channel expected to be dominant (in many models): $S \to b\bar{b}$

Targeted searches offer order of magnitude higher sensitivity than decay independent one

Higher sensitivity obtained for channels where hadronic Z decays could be used

Some details still to be sorted out, but three contributions being prepared for the report.

Thank you!