Searches for light exotic scalars at the e^+e^- Higgs factory

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Prospects for light exotic scalar measurements

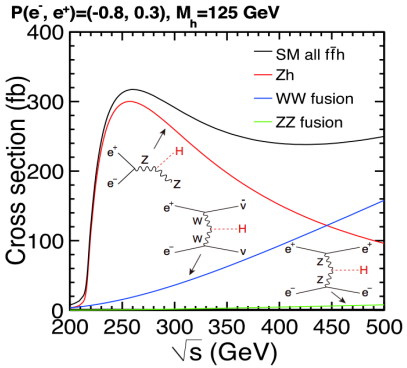
Outline:

1. Motivation
2. ILC and its experiments
3. Analysis framework
4. Search strategies
   - Decay mode independent
   - $S \to b\bar{b}$
   - Other decay channels
5. Summary and Conclusions

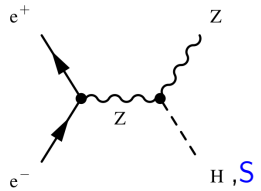
My own analysis focused on $S \to b\bar{b}$, but I also cover other recent ILD results for completness

e^+e^- Higgs factory

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



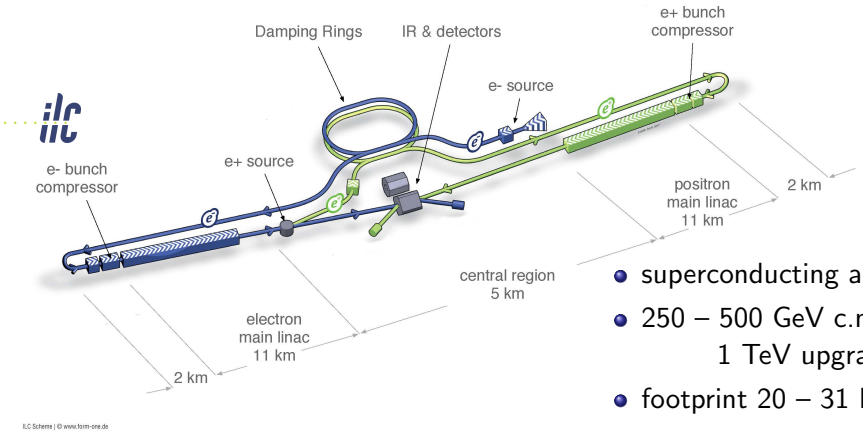
At 250 GeV we will focus on H_{125} production
in the ZH production channel (dominant below 450 GeV)



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

Production cross sections up to $\sim 10\%$ of $\sigma_{SM}(M_S)$, see backup

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

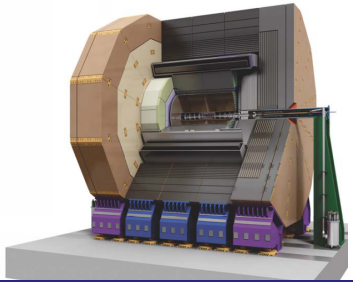
Baseline detector requirements

- 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

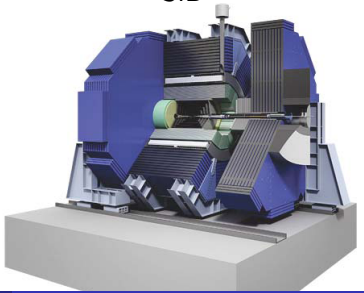
Two detailed ILC detector concepts optimized for particle flow event reconstruction

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

ILD



SiD



Analysis framework

Full simulation decay mode independent and $S \to b\bar{b}$ studies

Studies based on existing ILD Monte Carlo samples for SM processes at 250 GeV:

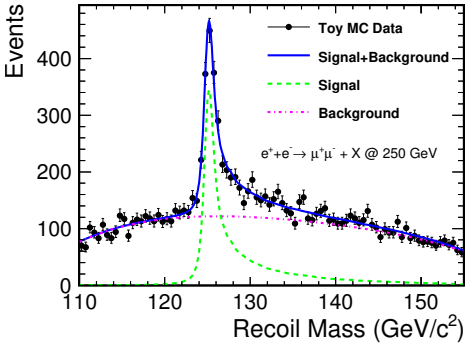
- generated with Whizard v.2.8.5,
- using default (SetA) ILC beam-spectrum,
- simulated and reconstructed using a full (GEANT 4) ILD detector simulation with ILD_l5_o2_v02 model and ILCSoft v02-02-01,
- processed using MARLIN modular framework for jet clustering and flavour tagging based on LCFIplus.

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 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)!

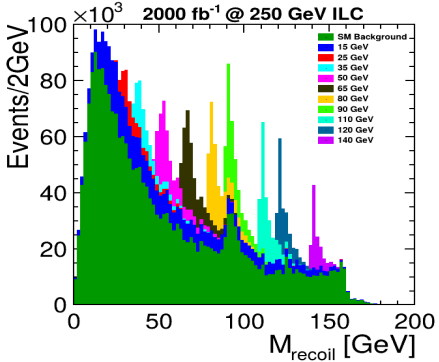
Decay mode independent search

New analysis

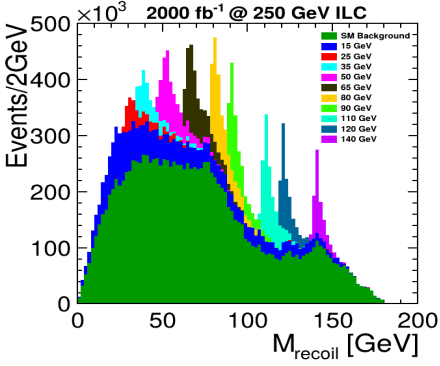
María Teresa Núñez Pardo de Vera (DESY) @ EPS-HEP'2025

Recoil mass spectrum from the full simulation before final cuts

$Z \to \mu^+\mu^-$



$Z \to e^+e^-$

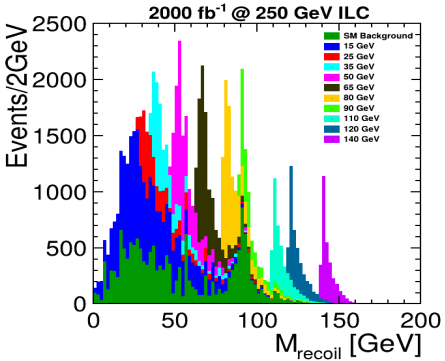


Much higher background in the electron channel due to Bhabha scattering.

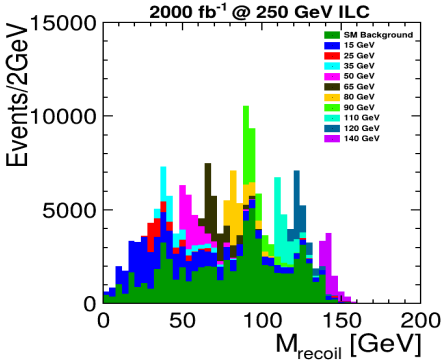
New analysis

Recoil mass spectrum after final selection based on event classification with MVA

$Z \to \mu^+\mu^-$



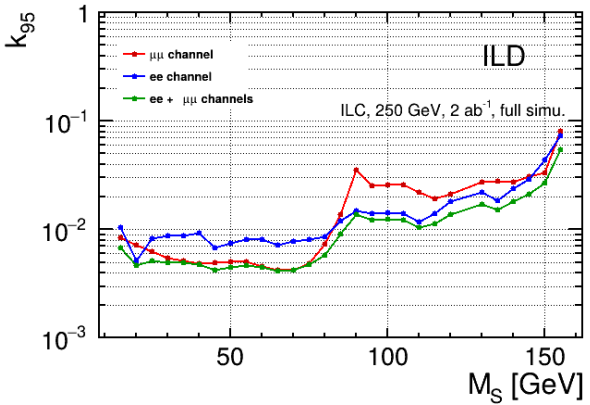
$Z \to e^+e^-$ (for 50 GeV scalar)



Two independent MVA algorithms trained to separate signal from 2f and 4f backgrounds

Results

Scalar decay independent search sensitivity for ILC running at 250 GeV



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

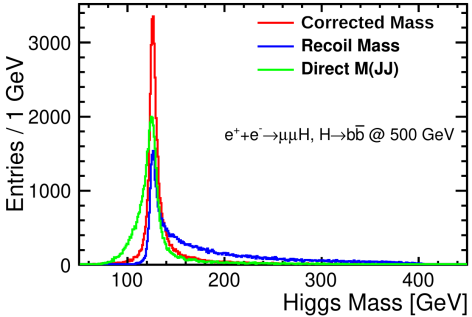
$$k = \frac{\sigma\,(e^+e^- \to Z\,S)}{\sigma^{SM}\,(e^+e^- \to Z\,H)|_{m_H=m_S}}$$

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

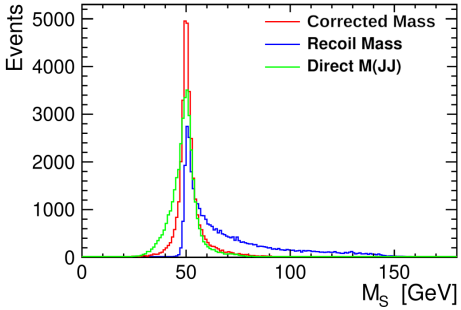
Event reconstruction

Looking at leptonic Z decays, $Z \to e^+e^-/\mu^+\mu^-$; huge W^+W^- background for hadronic ones
As in the 125 GeV Higgs boson reconstruction, event kinematics is much better constrained.

Full simulation for H_{125} at 500 GeV



Fast simulation for 50 GeV scalar at 250 GeV

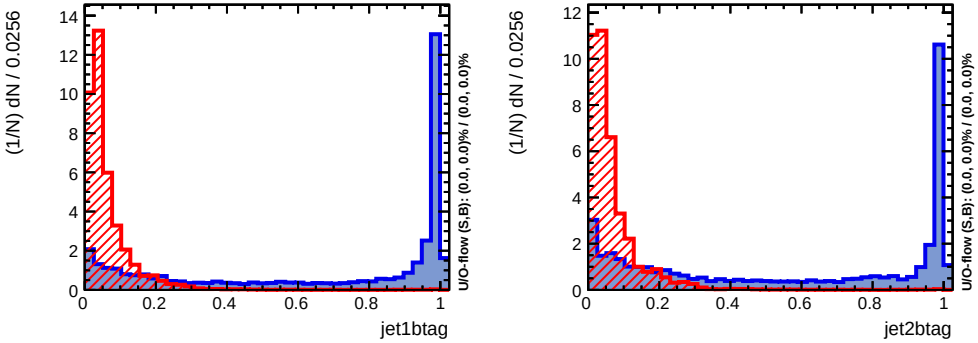


ILD-PHYS-PUB-2019-001

Flavour tagging

Tagging of b jets crucial for background suppression, but very simplified in fast simulation....
$\Rightarrow$ full simulation samples used for most reliable estimate of selection efficiency.

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

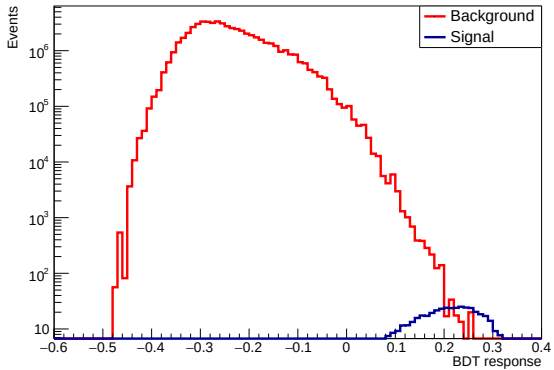


Event classification

BDT classifier
applied after very loose event preselection
(two electrons or muons, two hadronic jets)

Example for $e_L^- e_R^+$ polarization,
signal for scalar mass of $M_S = 50\,\text{GeV}$

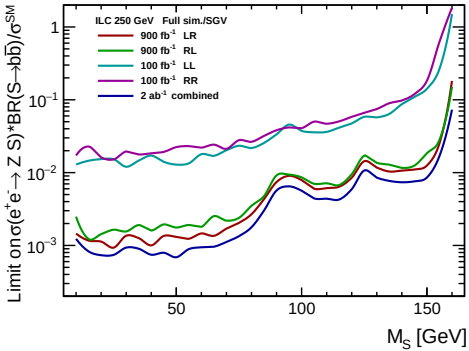
signal normalized to 1% of the $\sigma_{SM}(M_S)$



Huge background can be efficiently separated...

Results

Expected limits on the scalar production cross section (times $b\bar{b}$ branching ratio) extracted from the shape of the BDT response distribution:



Leptonic Z decays only. Full simulation analysis of hadronic Z decays still to be concluded...

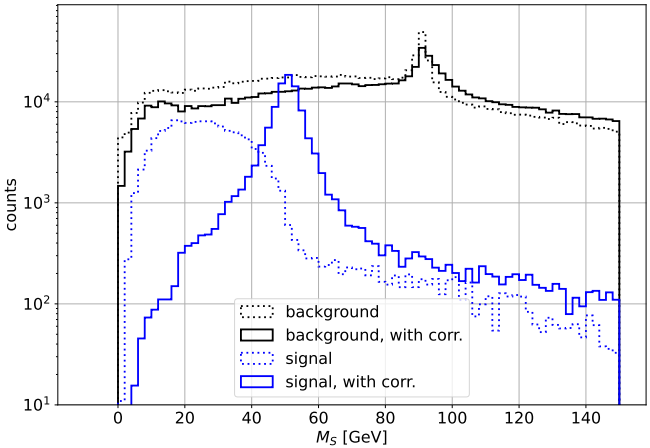
Event reconstruction

Kamil Zembaczyński (University of Warsaw)

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

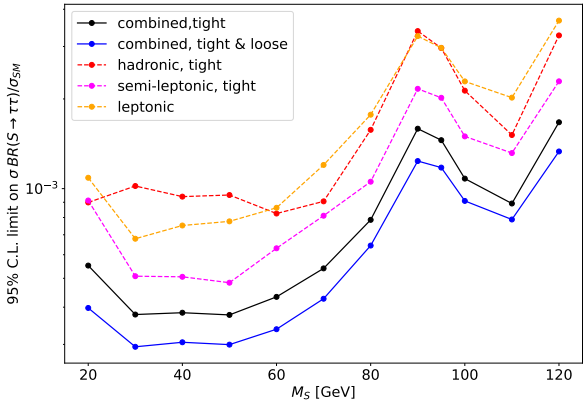
Signal for scalar mass of **50 GeV**. Normalized to 1% of the SM production cross section for the considered scalar mass.

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



Results

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

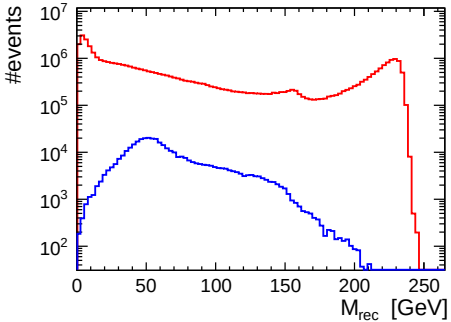
Marginal impact of normalization uncertainties (theory + lumi).

Event selection

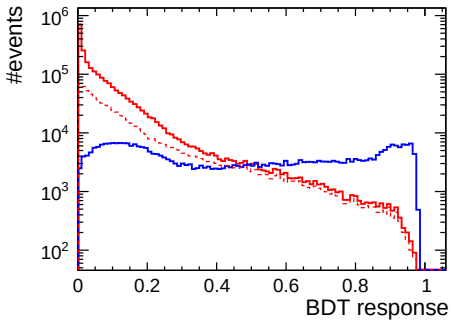
Kamil Zembaczyński (University of Warsaw)

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.



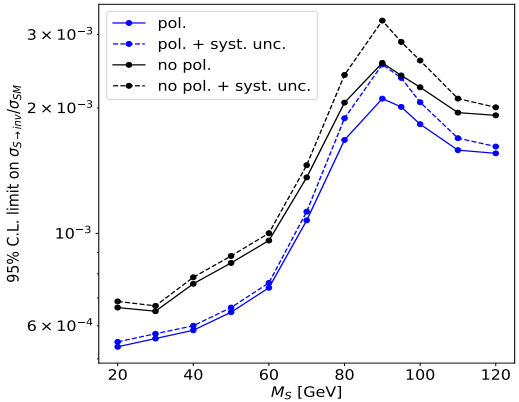
Signal normalized to 1% of SM cross section.



Dashed: $qq\ell\nu$ background.

Results

Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \text{inv})$
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 $\gamma\gamma$

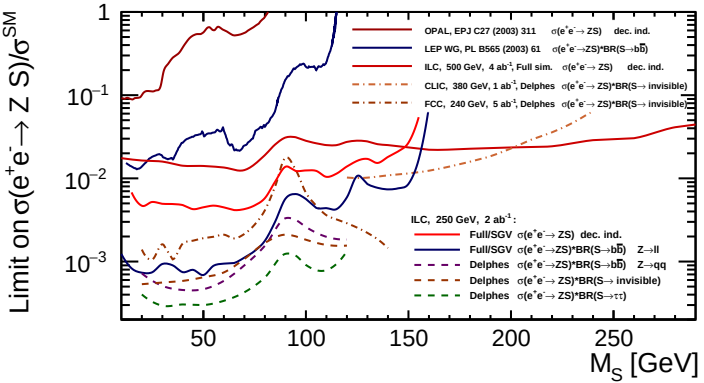
sample normalization: 0.2% for LR and RL
0.5% for LL and RR

Significant impact for $M_S \sim M_Z$

New ILD results

ECFA study report: arXiv:2506.15390

Presented ILD results were obtained within the ECFA Higgs/Top/EW factory study and submitted to the final report. Comparison with earlier results:



⇐ new ILD studies

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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Additional improvement expected when combining leptonic and hadronic Z decays (WIP)

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Light scalar decays to tau pairs seem a challenging scenario
But also results in most stringent limit on the cross section times branching ratio
promising discovery channel for models with enhanced $\tau^+\tau^-$ decays

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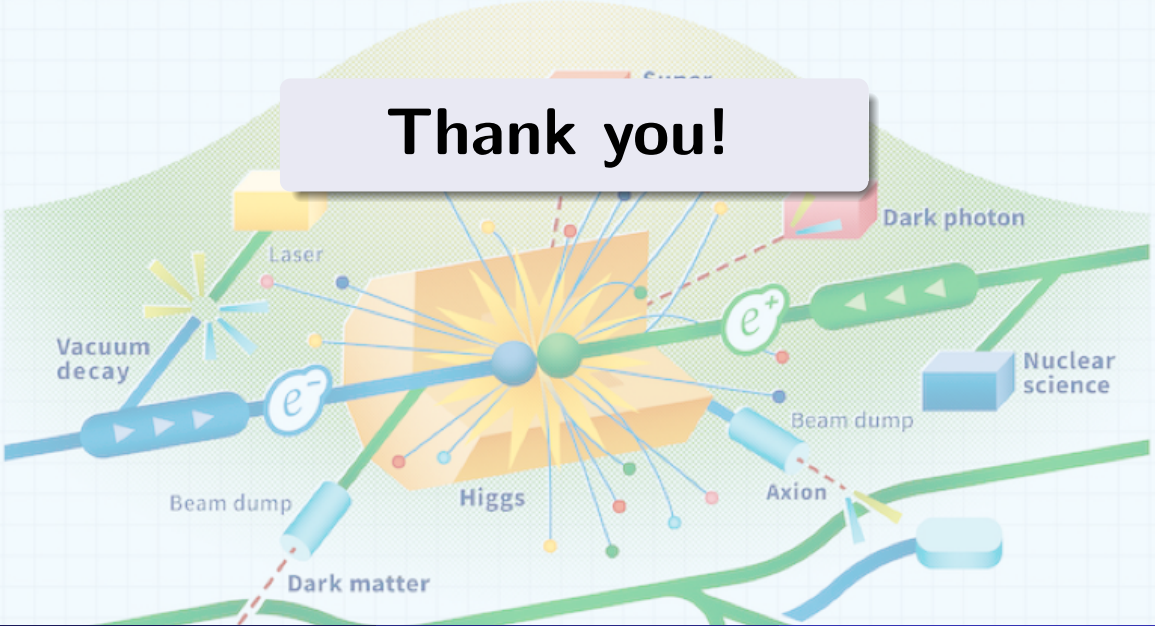
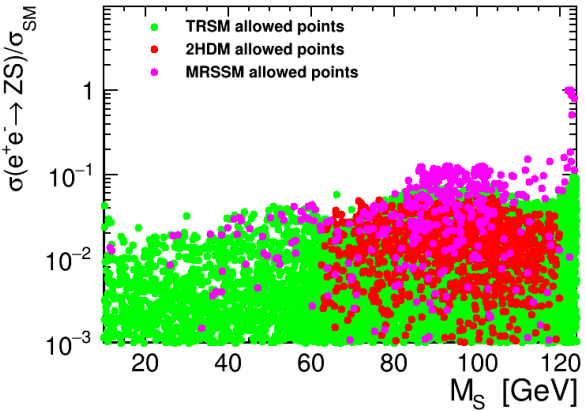
Presented studies were carried out in the framework of the **ILD concept** for the **ILC**
But the results should be quite general, applying to all 240–250 GeV e^+e^- machines...

Thank you!


Dark photon
Laser
Vacuum decay
e^+
e^-
Nuclear science
Beam dump
Beam dump
Higgs
Axion
Dark matter

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

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 $S \to \tau^+\tau^-$ and $S \to$ *invisible* studies

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.
$\tau^+\tau^-$ 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

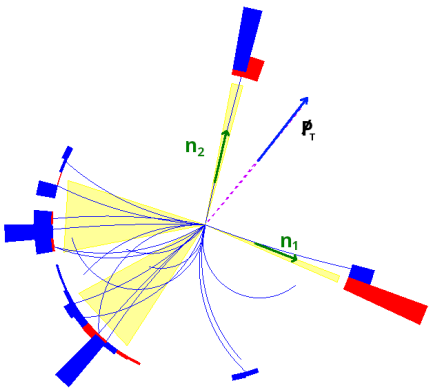
Total luminosity of $2\,\text{ab}^{-1}$, with $\pm 80\%/\pm 30\%$ polarisation for e^-/e^+. (H-20 scenario)

Fast detector simulation with Delphes ILCgen model.

$S \to \tau^+\tau^-$ event 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:

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

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

$S \to \tau^+\tau^-$ 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!

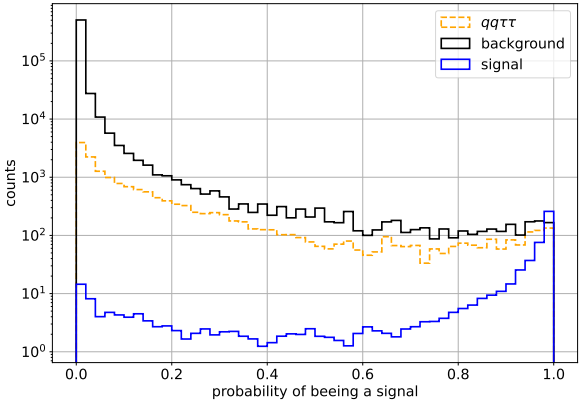
$S \to \tau^+\tau^-$ event classification

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



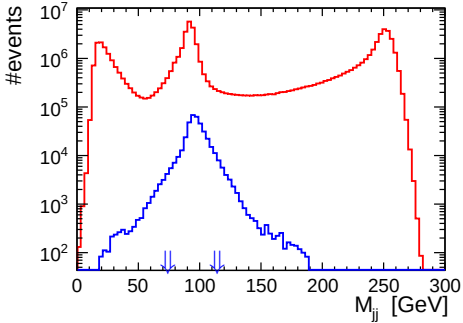
$S \rightarrow$ invisible event reconstruction

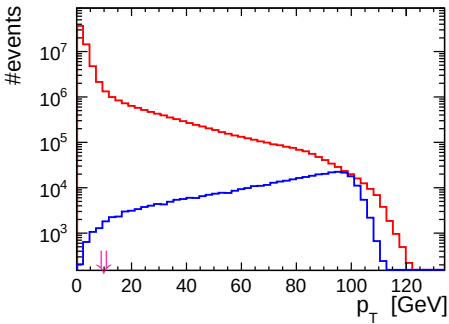
Kamil Zembaczyński (University of Warsaw)

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.

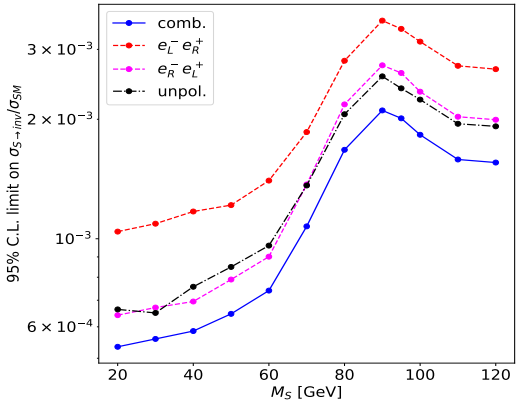




Signal normalized to 1% of SM cross section.

$S \to$ **invisible** **results**

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.