Searches for light exotic scalars in the $S \to b\bar{b}$ decay channel at future Higgs factories

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Prospects for light exotic scalar measurements

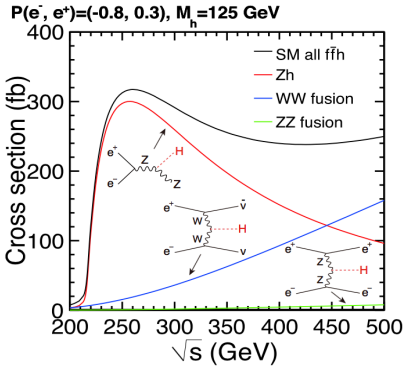
Outline:

1. Motivation
2. ILC and its experiments
3. Analysis framework
4. Conclusions

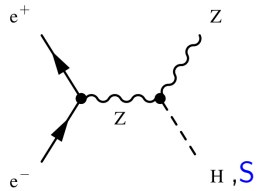
Results presented were obtained within the ILD concept study group.

e^+e^- Higgs factory

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



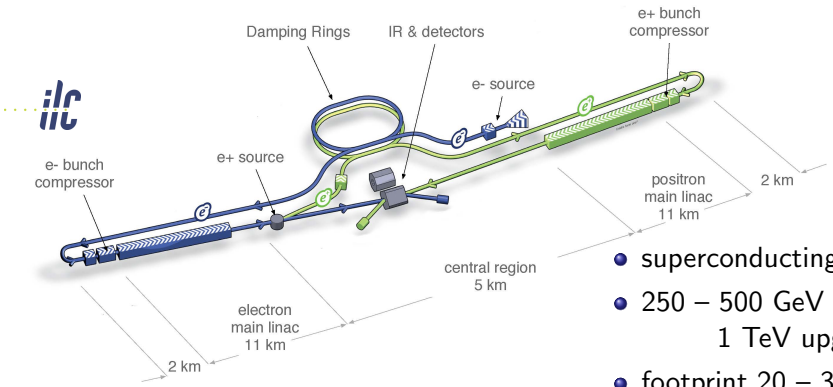
At 250 GeV we will focus on H_{125} production in the ZH production channel (dominant below 450 GeV)



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

Production cross sections up to few % of $\sigma_{SM}(M_S)$ allowed

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

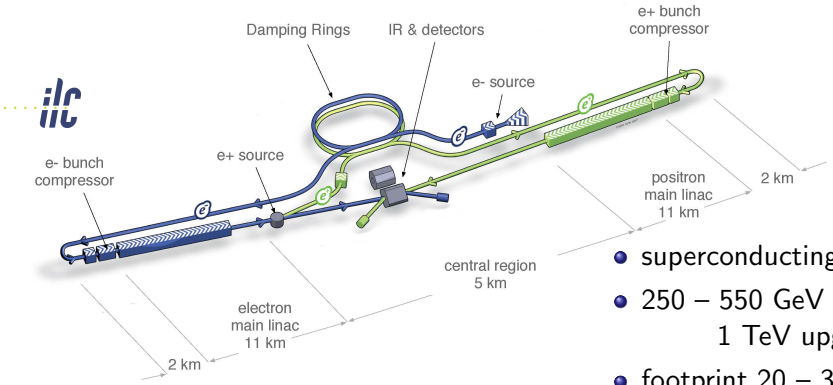


- superconducting accelerating cavities
- 250 – 500 GeV c.m.s. energy (baseline), 1 TeV upgrade possible
- footprint 20 – 31 km

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

International Linear Collider Technical Design (TDR) presented in 2013

Technology also considered for a Linear Collider Facility at CERN arXiv:2503.24049



- superconducting accelerating cavities
- 250 – 550 GeV c.m.s. energy (baseline), 1 TeV upgrade possible
- footprint 20 – 33 km
- polarisation for both e^- and e^+ (80%/60%)
- staged construction, starting as 250 GeV Higgs factory

Event simulation

Studies based on existing ILD Monte Carlo samples for SM processes at 250 GeV and 550 GeV:

- generated with Whizard v.2.8.5/v.3.1,
- using default (SetA) ILC beam-spectrum,
- simulated and reconstructed using
  a full (GEANT 4) ILD detector simulation/SGV Fast simulation
  with ILD_l5_o2_v02 model and ILCSoft v02-02-01,
- processed using MARLIN modular framework
  for jet clustering with Durham algorithm and flavour tagging based on LCFIplus.

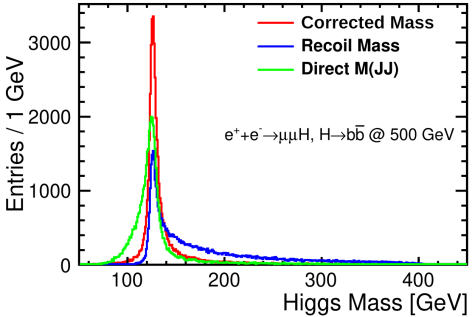
Signal samples, for scalar particle mass from 10 GeV up to 160 GeV for the 250 GeV scenario and from 20 GeV up to 460 GeV for the 550 GeV energy, were generated and processed with the same tools, but the detector simulation was done with SGV.

Total luminosity of $2\,\mathrm{ab}^{-1}/4\,\mathrm{ab}^{-1}$, with $\pm 80\%/\pm 30\%$ polarisation for e^-/e^+ (H-20 scenario).

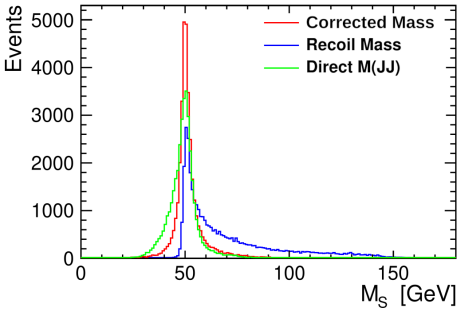
Event reconstruction

Looking at both leptonic ($Z \to e^+e^-/\mu^+\mu^-$) and hadronic ($Z \to q\bar{q}$) decays of the Z boson Kinematic constrains can be used to improve mass reconstruction, as for 125 GeV Higgs:

H_{125} at 500 GeV



50 GeV scalar at 250 GeV

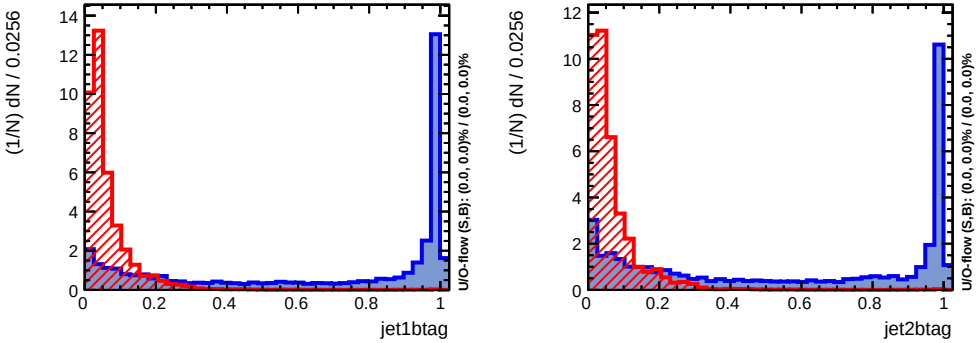


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Flavour tagging

Tagging of b jets crucial for background suppression
$\Rightarrow$ full simulation samples used for most reliable estimate of selection efficiency.

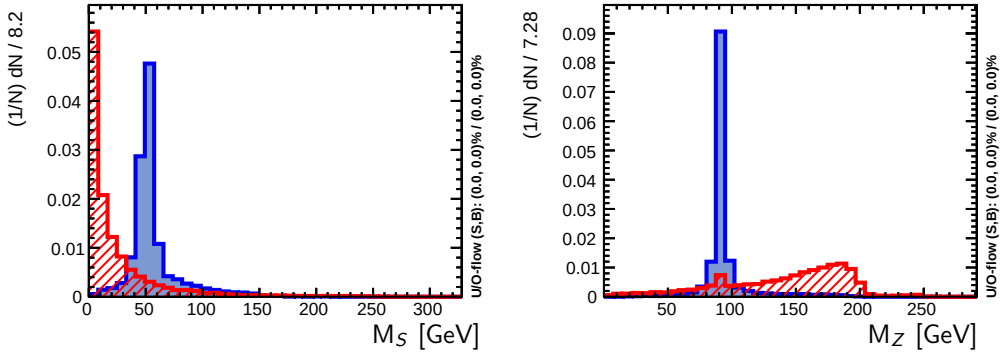
Clear separation of signal events from (mostly light flavour) SM backgrounds



Final state reconstruction

Reconstructed invariant mass distributions for the 50 GeV scalar candidate (pair of tagged b jets) and Z boson candidate (pair of leptons) for 250 GeV scenario.

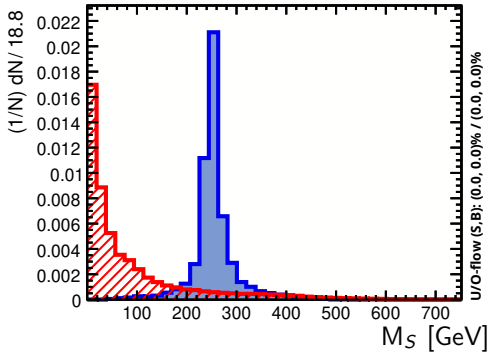
Clear peaks visible for signal events ⇒ efficient discrimination from SM backgrounds.

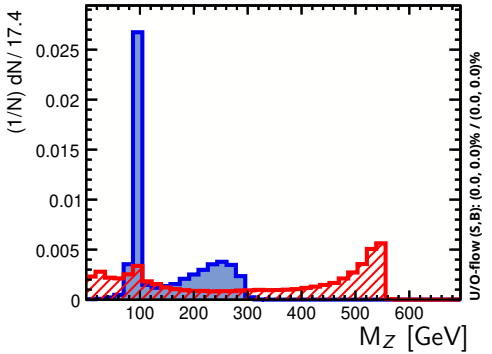


Final state reconstruction

Reconstructed invariant mass distributions for the 250 GeV scalar candidate (pair of tagged b jets) and Z boson candidate (pair of leptons) for the 550 GeV scenario.

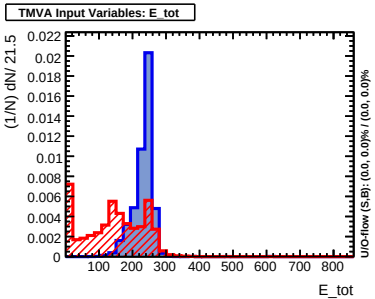
Clear peaks visible for signal events $\Rightarrow$ efficient discrimination from SM backgrounds.

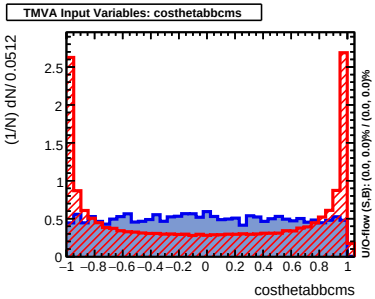


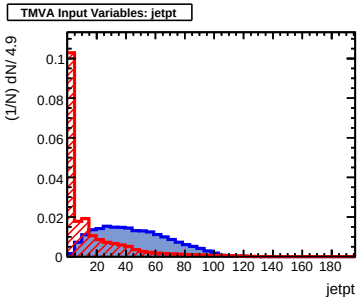


Event classification

Normalized distributions of some of the variables used for 50 GeV scalar selection, for 250 GeV running scenario and hadronic Z decays.

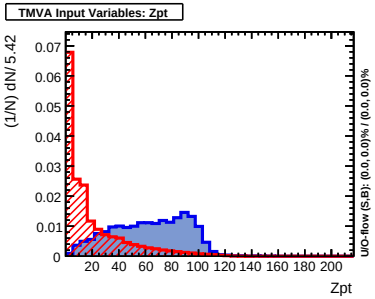


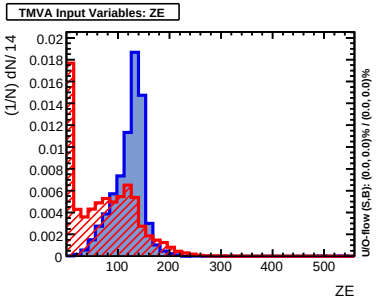


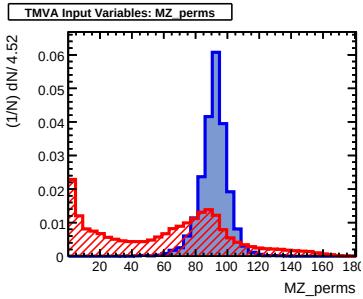


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Normalized distributions of some of the variables used for 50 GeV scalar selection, for 250 GeV running scenario and hadronic Z decays.







Event classification

A BDT classifier was trained using the following variables

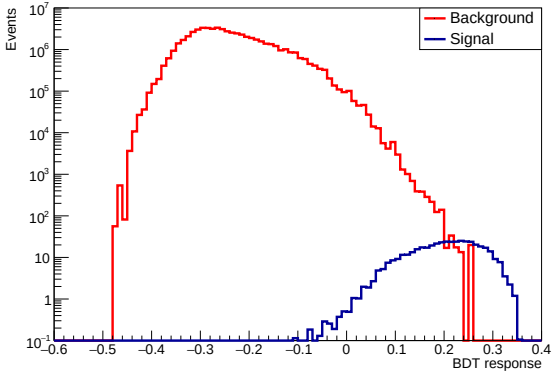
- Total energy
- Number of reconstructed electrons, muons and photons
- Transverse momentum of the jets
- Number of b-jets
- b-tagging response
- $\cos\theta$ of the b-jets
  in the reference frame of the scalar
- Reconstructed S and Z masses
  - based on lepton ID + b-tag
  - for hadronic events:
    also based on b-tag + kinematic fit
- Recoil mass
- transverse momentum of the Z
- Z energy

Event classification

250 GeV scenario
BDT classifier for the leptonic Z decays
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 $\sigma_{SM}(M_S)$



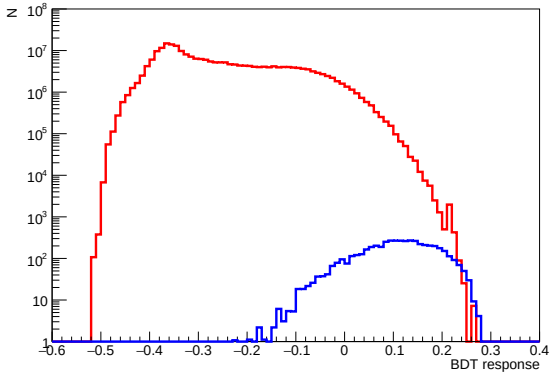
Huge background can be efficiently separated...

Event classification

250 GeV scenario
BDT classifier for the hadronic Z decays
applied after very loose event preselection
(four hadronic jets, two with b-tag)

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

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



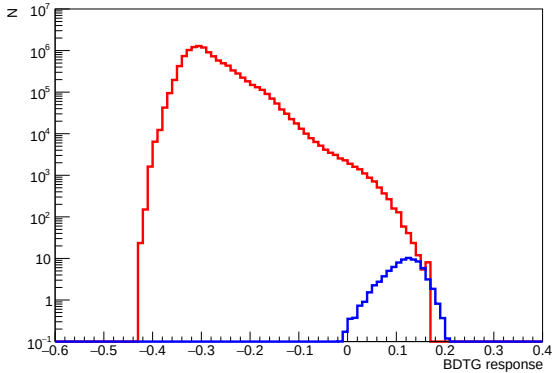
Huge background can be efficiently suppressed...

Event classification

550 GeV scenario
BDTG classifier for the leptonic Z decays
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 $M_S = 250\,\text{GeV}$

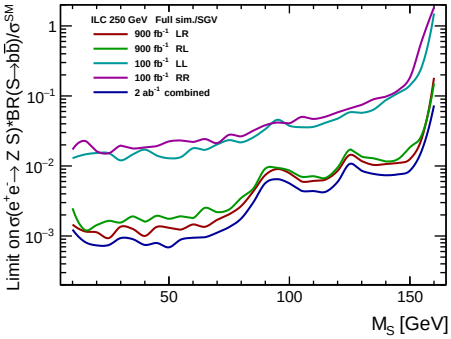
signal normalized to 1% of the $\sigma_{SM}(M_S)$

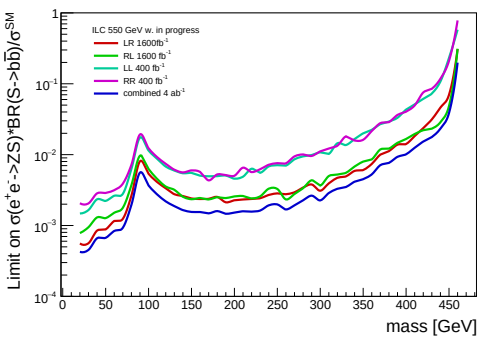


Huge background can be efficiently suppressed...

Results

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

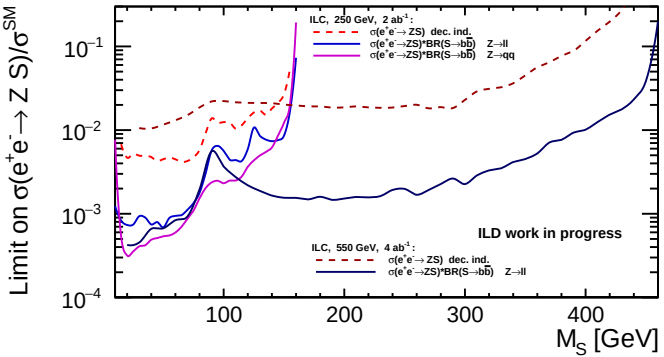




Leptonic Z decays, limits for different polarizations.

Results

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



For 550 GeV leptonic Z decays only. Full simulation analysis of hadronic Z decays still to be concluded...

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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BDT classification and significance calculation based on the shape of the BST response distribution allows for setting stringent limits on production cross section times branching ratio.

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In $b\bar{b}$ decay channel cross sections down to $\mathcal{O}(10^{-3})$ of the SM cross section can be probed.
For 550 GeV, additional improvement expected when combining leptonic and hadronic Z decays (WIP)

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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 240–250/550 GeV e^+e^- machines...

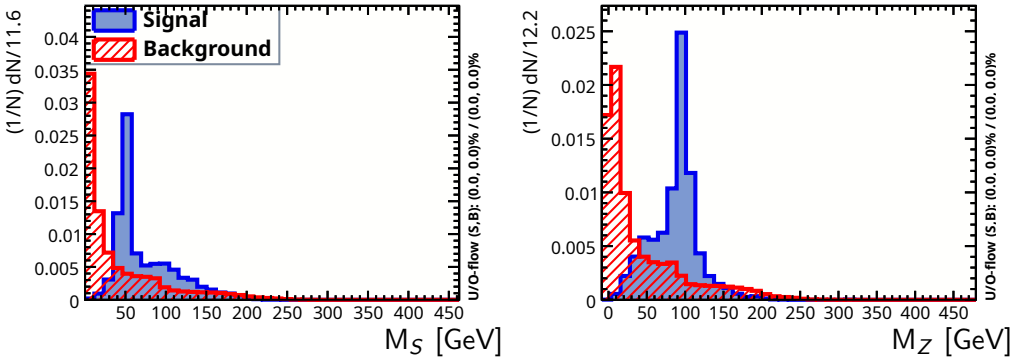
Thank you!


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

Final state reconstruction for hadronic Z decays

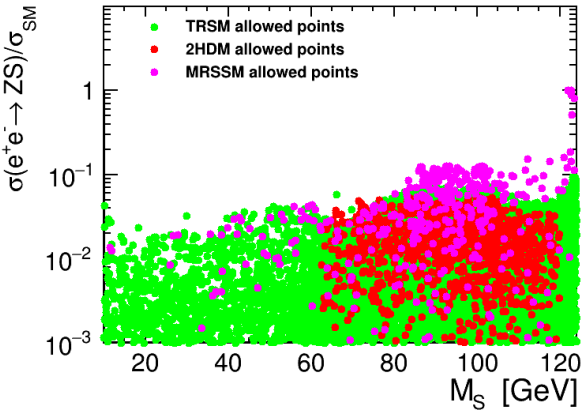
Reconstructed invariant mass distributions for the scalar candidate (pair of tagged b jets) and Z boson candidate (pair of leptons) for 250 GeV scenario.

Clear peaks visible for signal events ⇒ efficient discrimination from SM backgrounds.



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

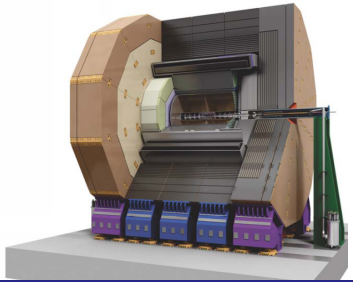
Baseline detector requirements

- Track momentum resolution: $\sigma_{1/p_t} = 2 \cdot 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \cdot 10^{-3}/(p_t\ \sin^{1/2}\Theta)$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\,\mu m\ \mathrm{GeV}/(p\ \sin^{3/2}\Theta)$
- 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

