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

Teresa Núñez - DESY

- Motivation
- Light exotic scalar searches:
  - decay model independent
  - based on different decay channels
- Outlook and conclusions

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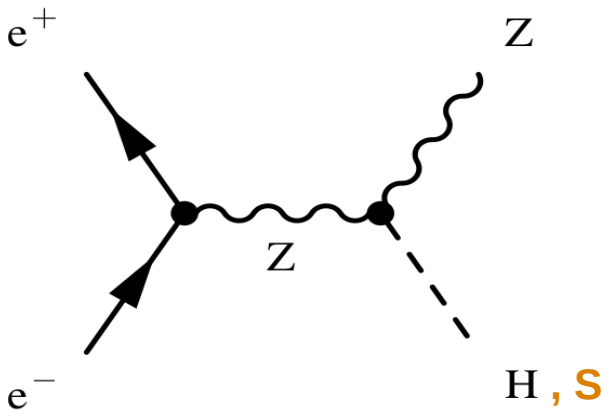
Motivation

Light exotic scalar are predicted by many BSM models and not excluded by current experimental and theoretical constraints

Similar to the Higgs-strahlung, dominant Higgs production channel for $\sqrt{s}$ below 450 GeV, …



… extra light scalars could also be produced in a scalar-strahlung process

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Motivation (ctd.)

Higgs factories are best suited for searching at new scalars in the process $e^+e^- \rightarrow ZS^0$

- Light scalars searches at future e^+e^- colliders were only partially studied so far
- More work is needed to understand the experimental challenges and prospects
- Light scalars searches were selected as one of the focus topics of the ECFA Higgs, electroweak and top factory study

Different search strategies:

- independent of the S^0 decay mode (based on recoil mass)
- S^0 decaying to $b\bar{b}, \tau\bar{\tau}$, W^+W^- or invisible

Different detector simulation and reconstruction procedures:

- Full detector simulation and reconstruction
- Fast detector simulation and reconstruction: SGV and DELPHES fast simulations

ILD@ILC 250 GeV assuming the H-20 running scenario:

arXiv:1506.07830

- P(e-,e+)=(-80%,+30%) 0.9ab^{-1}, P(e-,e+)=(+80%,-30%) 0.9ab^{-1}
- P(e-,e+)=(-80%,-30%) 0.1ab^{-1}, P(e-,e+)=(+80%,+30%) 0.1ab^{-1}

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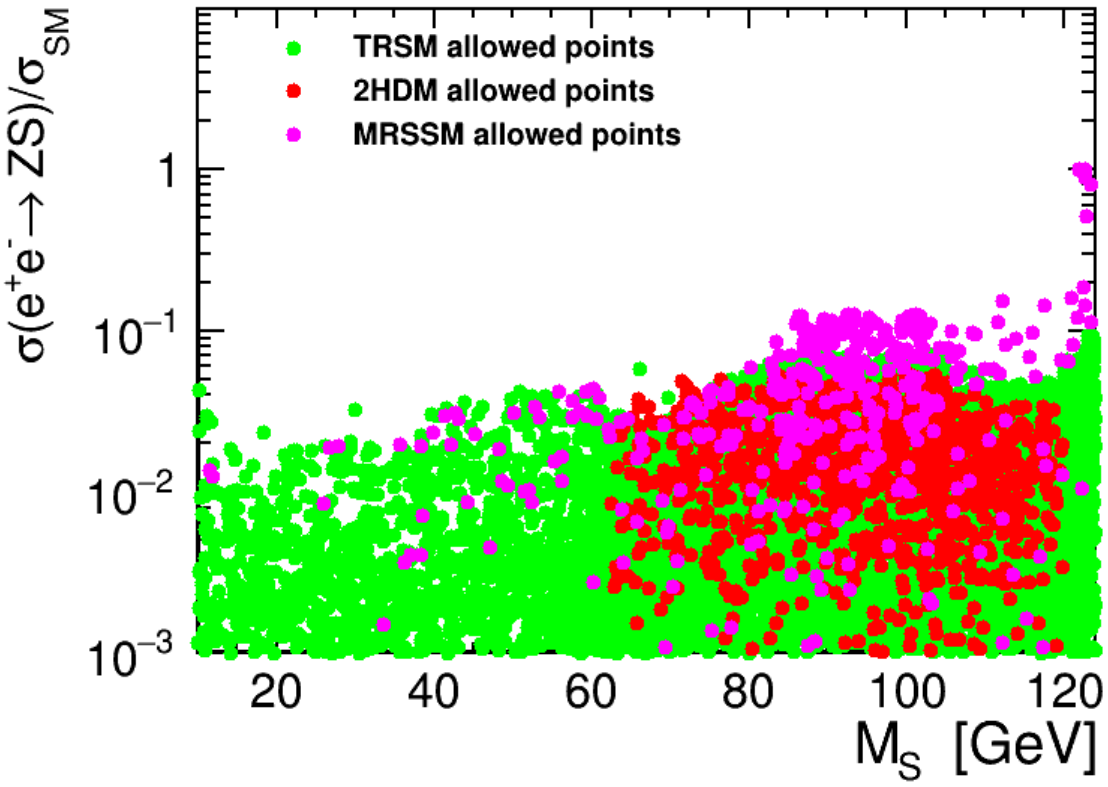
Motivation (ctd.)

Benchmark points not excluded by current experimental and theoretical constrains for three selected models



Allowed cross section values for the scalar-strahlung process at 250 GeV Higgs factories

Values relative to the SM predictions for the Higgs boson production at the given mass

arXiv:2209.10996 arXiv:2305.08595

arXiv:2309.17431

arXiv:1511.09334

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Decay model independent search

Model independent searches are based on the recoil of the new scalar against the Z

Independent fo the S^0 decay mode

Studies were performed using the full detector simulation and reconstruction procedures of the ILD at the ILC for $\sqrt{s}$ = 250 GeV

- Searches done for any mass and based on the recoil of the scalar against the Z
- Focused on the decays of the Z to two muons and two electrons

Samples:

- Background full detector simulation and reconstruction
- Signal detector simulation done by SGV fast simulation, full detector reconstruction.

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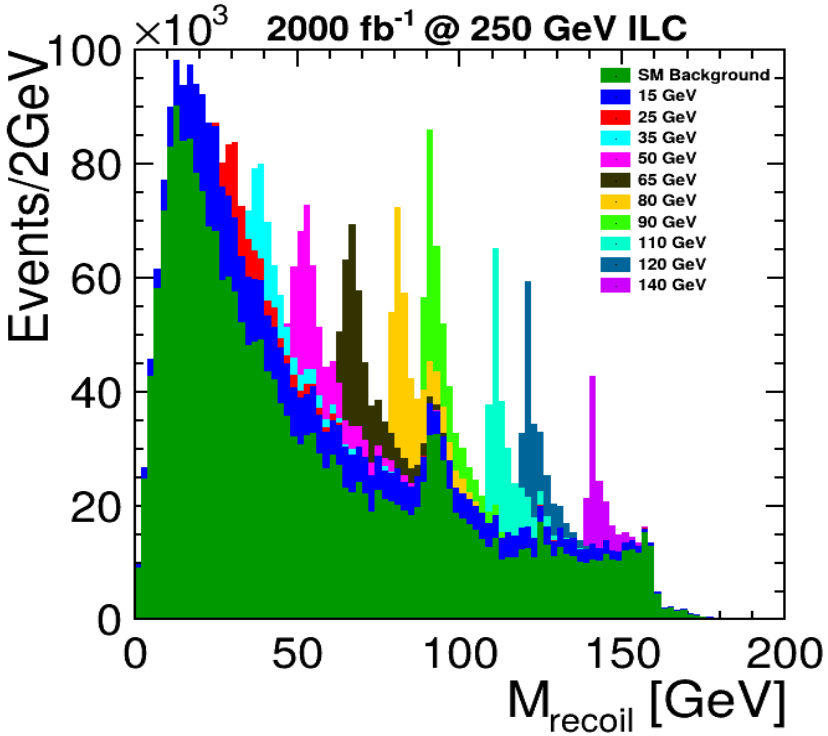
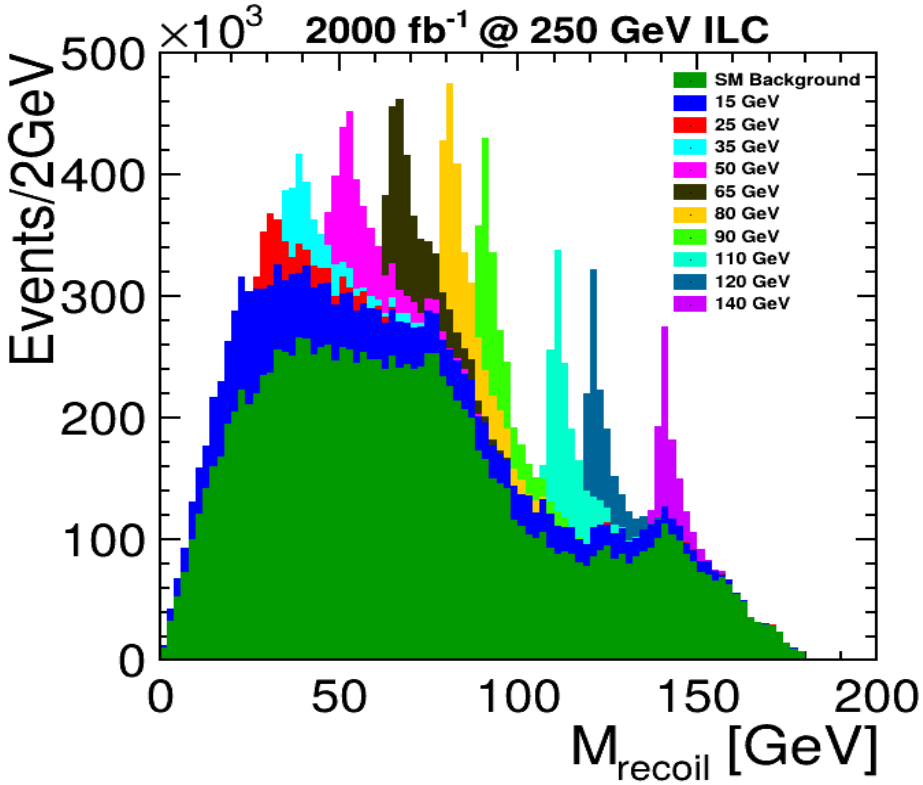
Decay model independent search (ctd.)

Recoil mass spectrum: signal vs background



Before final cuts



$e^+e^- \rightarrow ZS^0 \rightarrow \mu^+\mu^- S^0$

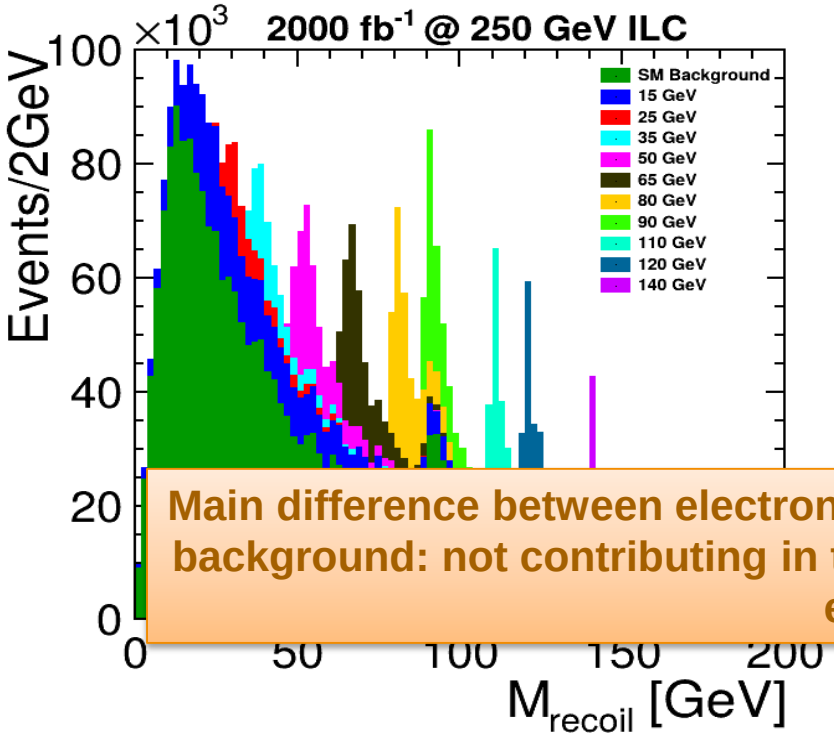
$$M_{rec}^2 = (\sqrt{s} - E_{ll})^2 - \left|\vec{P}_{ll}\right|^2$$

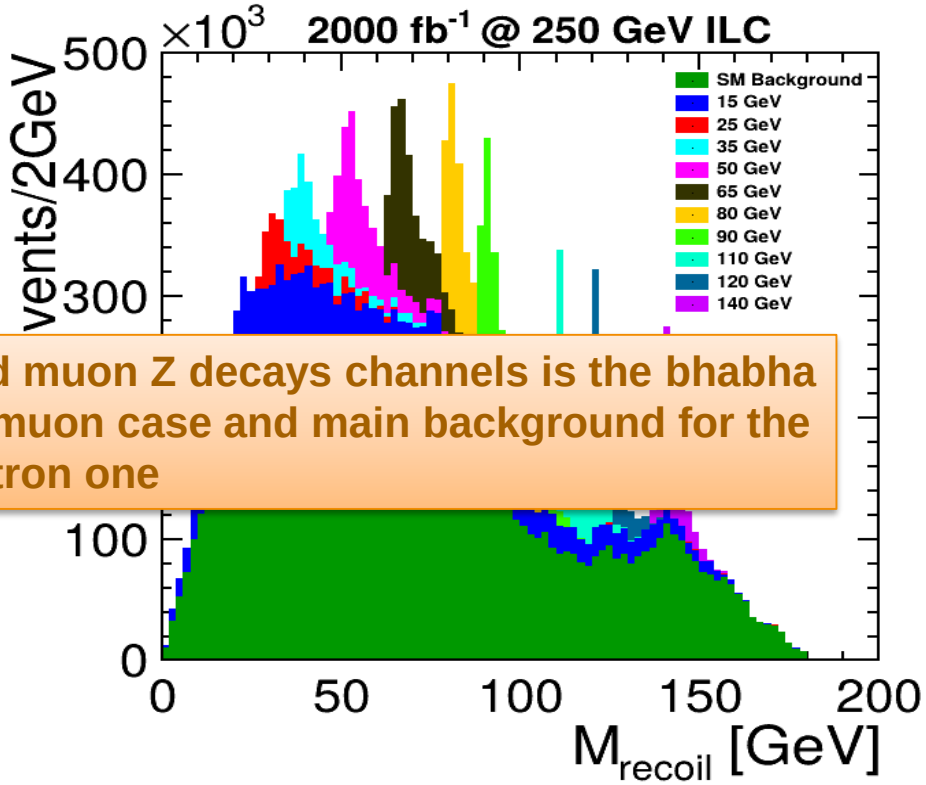
$e^+e^- \rightarrow ZS^0 \rightarrow e^+e^- S^0$

Decay model independent search (ctd.)

Recoil mass spectrum: signal vs background

Before final cuts





Main difference between electron and muon Z decays channels is the bhabha background: not contributing in the muon case and main background for the electron one

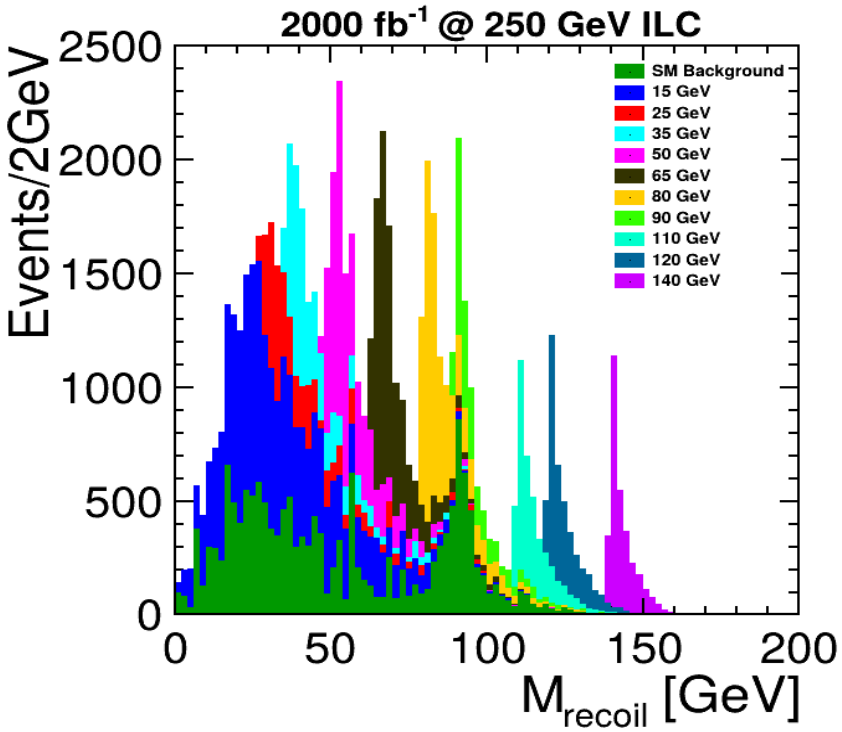
$e^+e^- \rightarrow ZS^0 \rightarrow \mu^+\mu^- S^0$

$$M^2_{rec} = (\sqrt{s} - \mathrm{E}_{ll})^2 - \left|\vec{P}_{ll}\right|^2$$

$e^+e^- \rightarrow ZS^0 \rightarrow e^+e^- S^0$

Decay model independent search (ctd.)

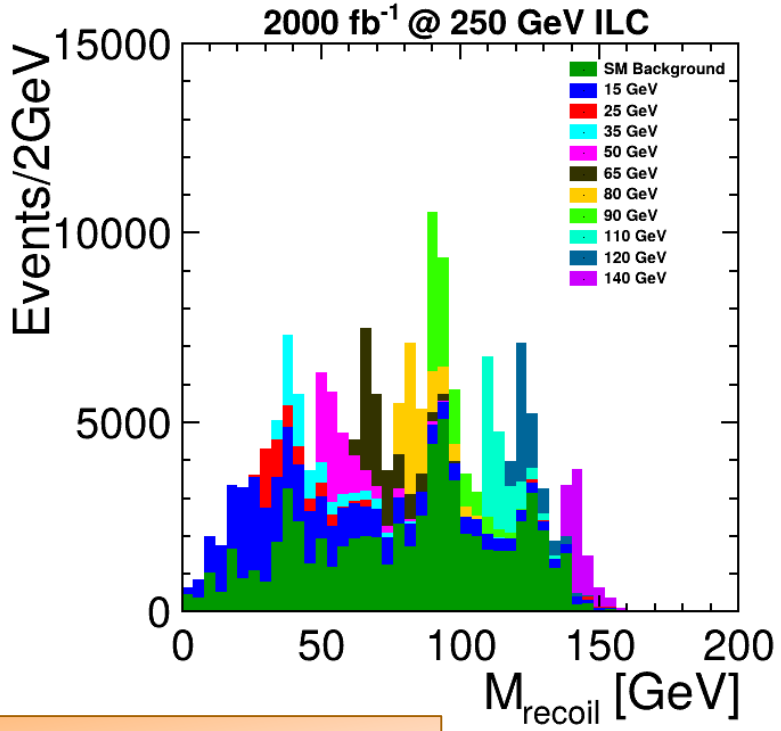
Recoil mass spectrum: signal vs background



$e^+e^- \rightarrow ZS^0 \rightarrow \mu^+\mu^- S^0$

$$M_{rec}^2 = (\sqrt{s} - E_{ll})^2 - \left|\vec{P}_{ll}\right|^2$$

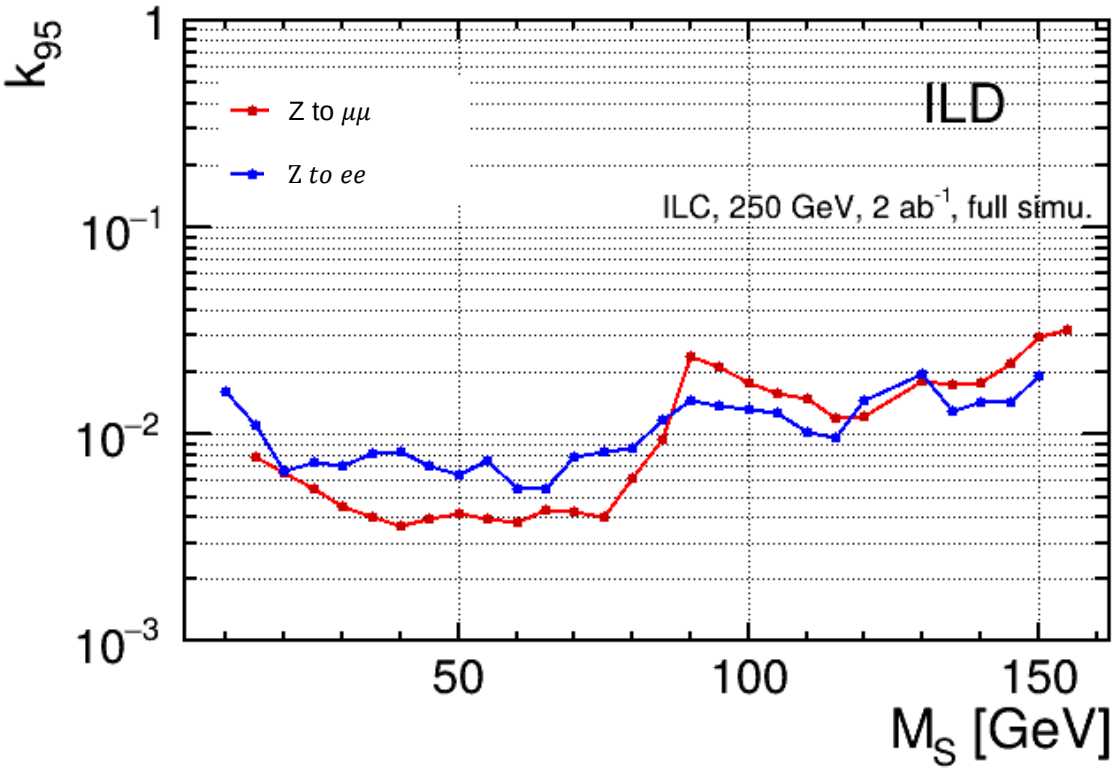
After all cuts
(for scalar mass 50 GeV)



$e^+e^- \rightarrow ZS^0 \rightarrow e^+e^-S^0$

Decay model independent search (ctd.)

Scalar search sensitivity for ILC @ 250 GeV

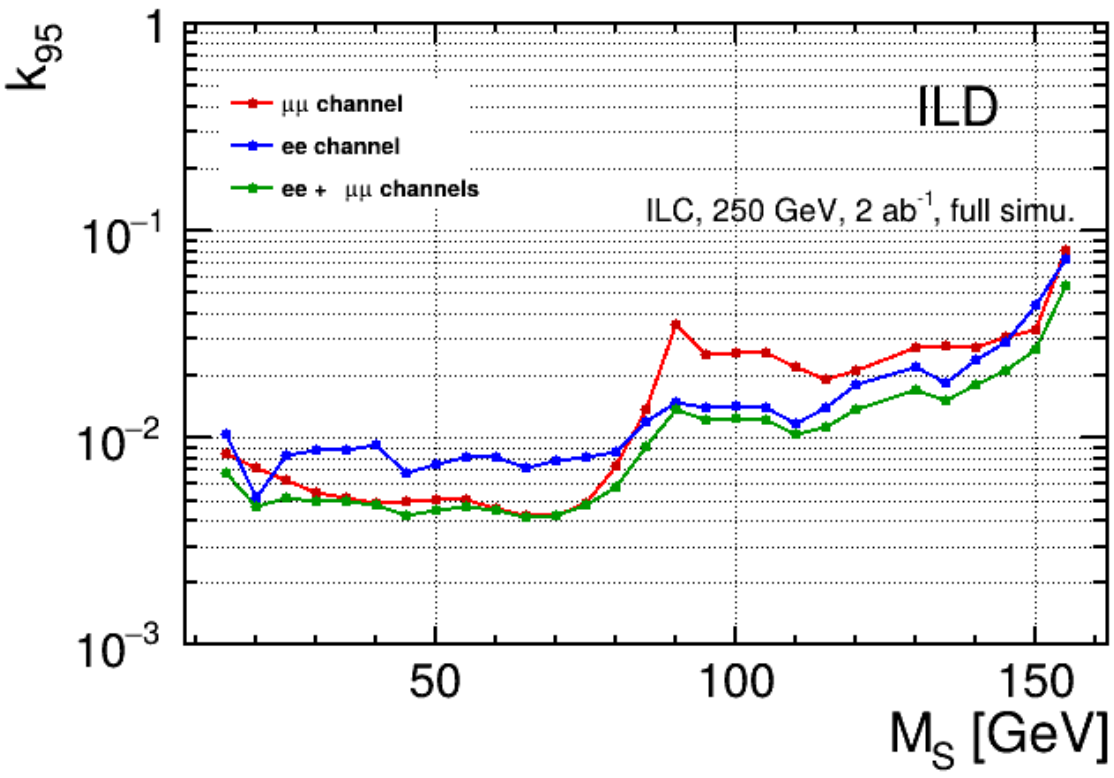


Scalar production cross section relative to SM Higgs boson production cross section at given mass

Limits computed based on the recoil mass distributions using fractional event counting

Decay model independent search (ctd.)

Scalar search sensitivity for ILC @ 250 GeV

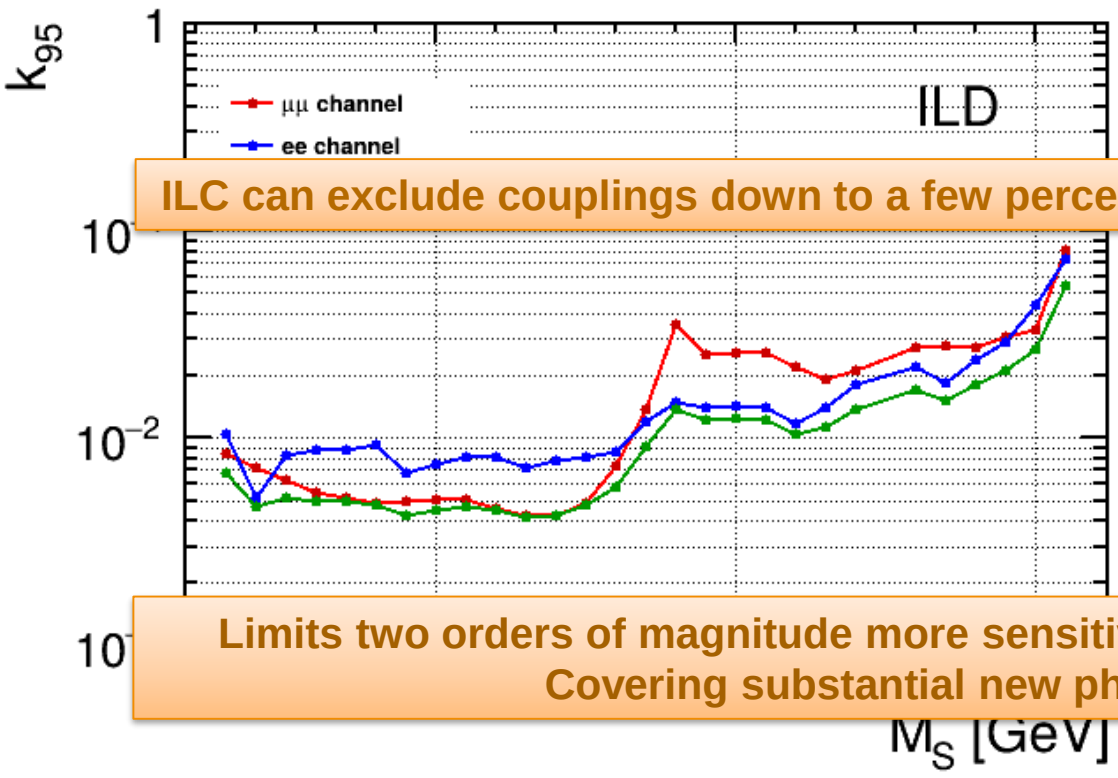


Scalar production cross section relative to SM Higgs boson production cross section at given mass

ee and $\mu\mu$ channels combined using likelihood ratio statistics applied to each bin used by the fractional event counting

Decay model independent search (ctd.)

Scalar search sensitivity for ILC @ 250 GeV



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

ILC can exclude couplings down to a few percent of the SM-Higgs equivalent

ee and $\mu\mu$ channels combined using likelihood ratio statistics applied to each bin used by the fractional event counting

Limits two orders of magnitude more sensitive than the ones from LEP
Covering substantial new phase space

Search in $b\bar{b}$ channel

For many BSM scenarios the coupling structure of the new exotic scalars is similar to that of the SM Higgs boson … hence …

Dominant decay channel for the light scalars (below 125 GeV)

Two studies performed for 250 GeV ILC scenario for leptonic and hadronic Z boson decays

$e^+e^- \rightarrow ZS^0 \rightarrow ll\, b\bar{b}$

- Full detector simulation for background and SGV fast detector simulation for signal
- Full reconstruction procedures of the ILD at the ILC
- Avoid huge background from hadronic W^+W^- events

$e^+e^- \rightarrow ZS^0 \rightarrow q\bar{q}b\bar{b}$

- Background and signal samples produced with Whizard
- Detector simulation and reconstruction with Delphes fast simulation
- Profit from higher Z branching ratio despite much higher background

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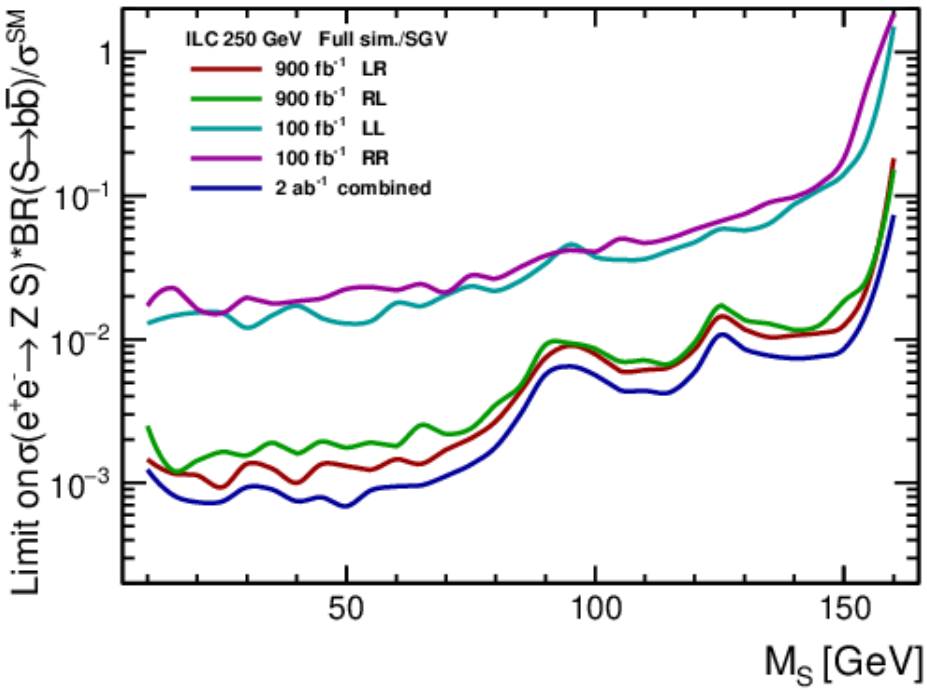
Search in $b\bar{b}$ channel: leptonic Z decays

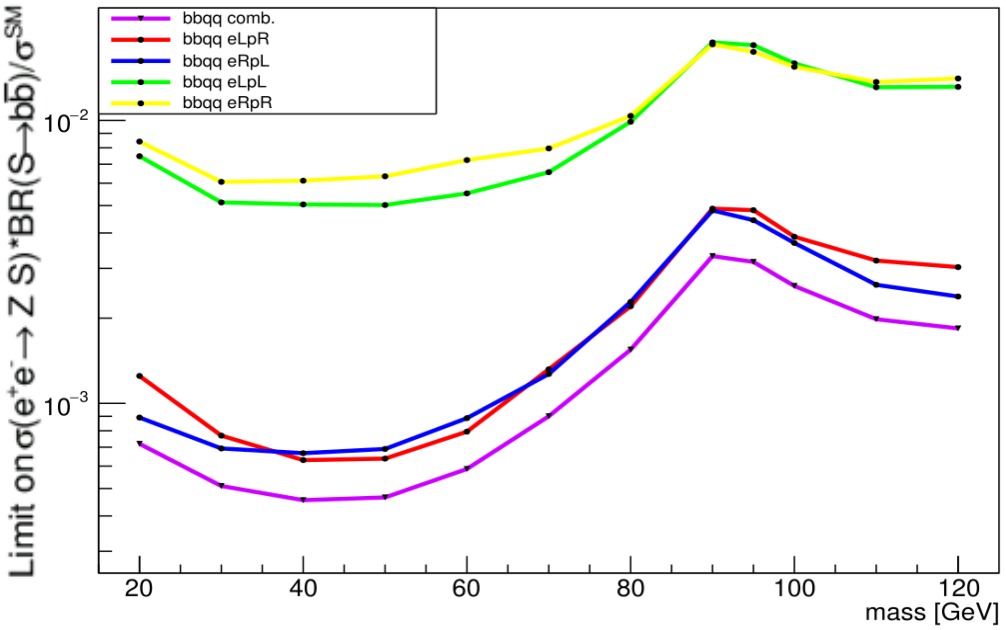
Exclusion limits on the ratio of the new scalar cross section times branching ratio to $b\bar{b}$, to the SM Higgs production cross scetion for each beam polarisation and combined



About one order of magnitude increase in sensitivity with respect to model-independent study, assuming that decays of the new scalar to $b\bar{b}$ dominate

Search in $b\bar{b}$ channel: hadronic Z decays

Exclusion limits on the ratio of the new scalar cross section times branching ratio to $b\bar{b}$, to the SM Higgs production cross section for each beam polarisation and combined



Improved sensitivity with respect to leptonic Z decays due to higher Z branching ratio

Search in $\tau\bar{\tau}$ channel

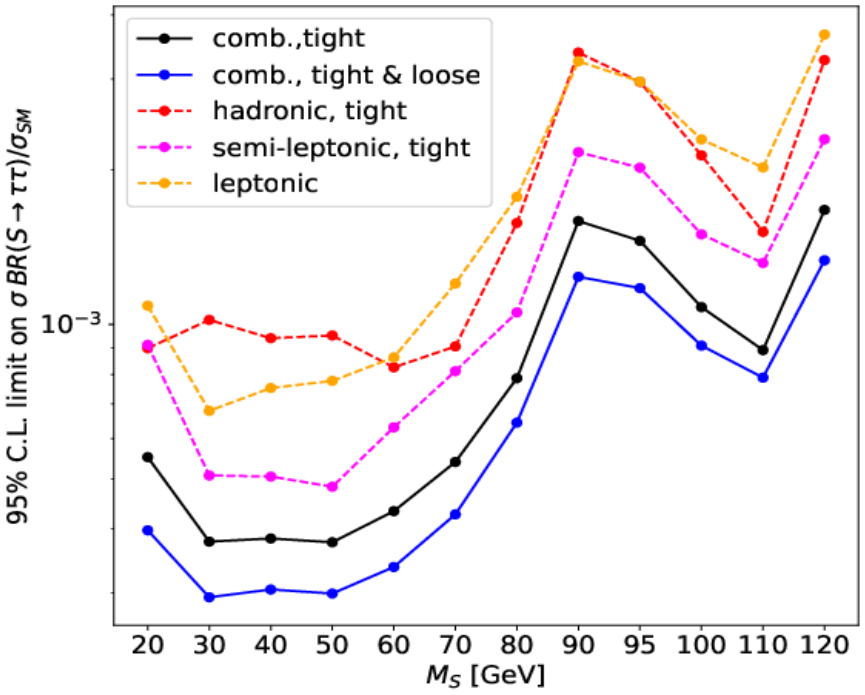
A new scalar with mass about 95 GeV and enhanced branching ratio to $\tau\bar{\tau}$ could explain some of the discrepancies from SM predictions in LEP and LHC data (arXiv:2203.13180)

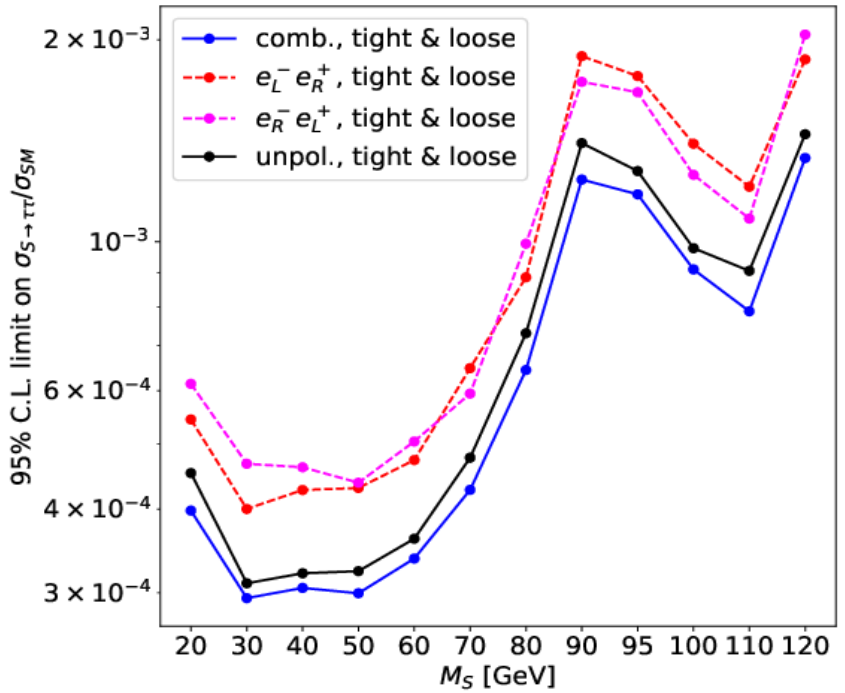
- Study performed for 250 GeV ILC scenario
- Detector response for background and signal samples uses DELPHES fast simulation
- Hadronic, semi-leptonic and leptonic τ-pair decays were considered in signal events

$$e^+e^- \rightarrow ZS^0 \rightarrow q\bar{q}\ \tau\bar{\tau}$$

- Tight selection: two identified τ candidates as an isolated lepton or hadronic jet with τ-tag
- Loose selection (hadronic and semi-leptonic decays): one identified τ candidate and three untagged hadronic jets

Search in $\tau\bar{\tau}$ channel (ctd.)





- Best results for tight semi-leptonic selection (high statistics and relatively low background levels)
- Including loose selection improves the limits by 20-30%

- Combination of four polarisations from H-20 scenario about a 10% improvement with respect to same integrated luminosity for unpolarised beams

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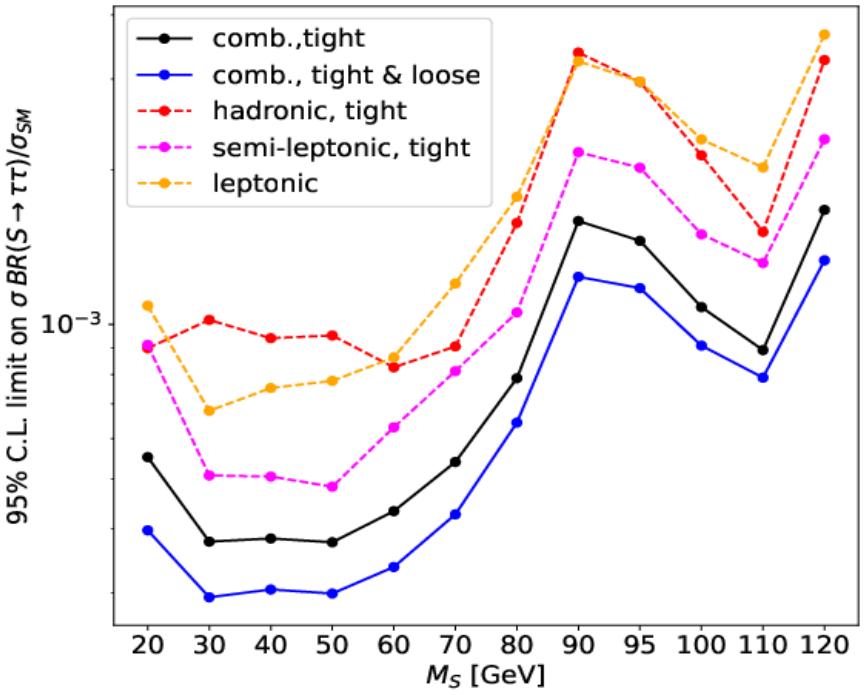
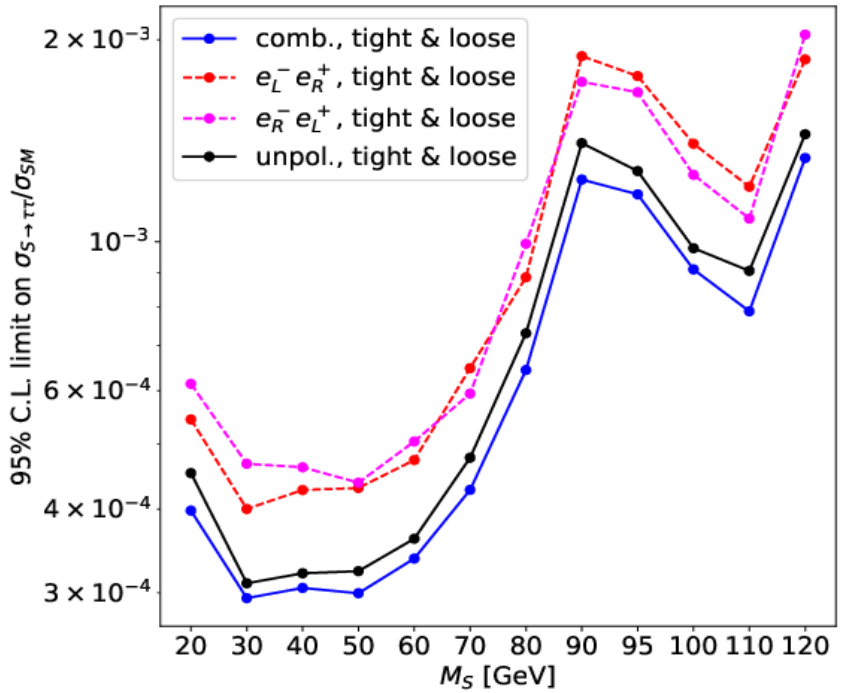
Search in $\tau\bar{\tau}$ channel (ctd.)





- Best resu… (high sta… levels)
- Including loose selection improves the limits by 20-30%

Limits stronger than the ones for $b\bar{b}$ channel (assuming the scalar branching ratio of the order of 10% or more)

…rom H-20… …ht with respect to same integrated luminosity for unpolarised beams

Assuming this scalar decay to dominate, sensitivity improves over an order of magnitude with respect to model independent searches

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Search in W^+W^- channel

Study based on the Two-Real-Singlet-Model (TRSM):
SM scalar sector enhanced by two additional singlets obeying a $Z_2 \oplus Z_2$ symmetry

Parameter space constrained by LHC 125 GeV Higgs boson measurements … but …
sizable production cross sections at future Higgs factories not ruled out

- Two fermion final states, expected to dominate light TRSM scalar decays, already covered by previous analysis
- Analysis focused on the feasibility of observing the $S \to W^+W^-$ decay at higher scalar masses

$e^+e^- \to ZS^0 \to ZWW \to \mu^+\mu^- e\bar{\nu}_e q\bar{q}$

- Process simulated in the TRSM model with an additional 140 GeV scalar
- Analysis simplified by using a final state matching in an unique way to Z, W^+ and W^-

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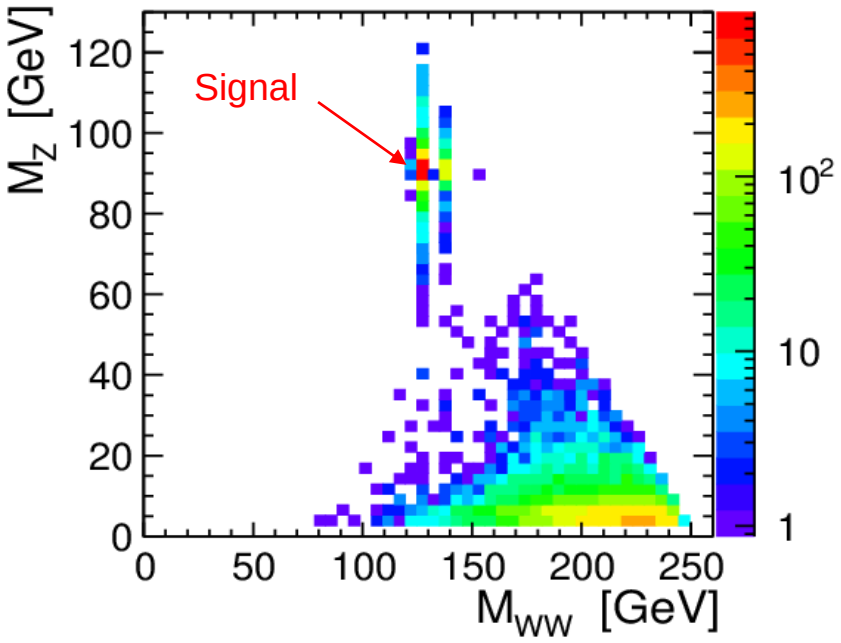
Search in W^+W^- channel (ctd.)

Invariant mass of the Z boson candidate vs invariant mass of the W^+W^- pair

Even after blurring from detector resolution, separation of scalar-strahlung process in the W^+W^- decay channel should be possible with high efficiency



MC studies indicates that observation of the new scalar production through the scalar-strahlung process with decay to W+W- should be feasible at a 250 GeV Higgs factory for scalar masses between 125 and 150 GeV

By exploring the leptonic Z decay, expected limits on the production cross section times BR(S→W^+W^-) should be comparable to those obtained in the $b\bar{b}$ channel

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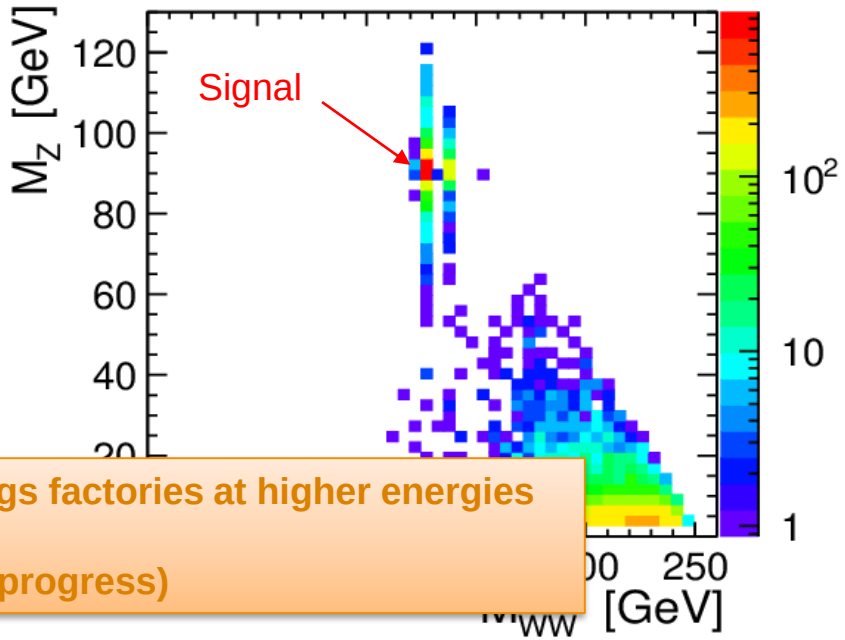
Search in W^+W^- channel (ctd.)

Invariant mass of the Z boson candidate vs invariant mass of the W^+W^- pair



Even after blurring from detector resolution, separation of scalar-strahlung process in the W^+W^- decay channel should be possible with high efficiency

Highly promising running Higgs factories at higher energies

(Work in progress)

MC studies indicates that observation of the new scalar production through the scalar-strahlung process with decay to W^+W^- should be feasible at a 250 GeV Higgs factory for scalar masses between 125 and 150 GeV

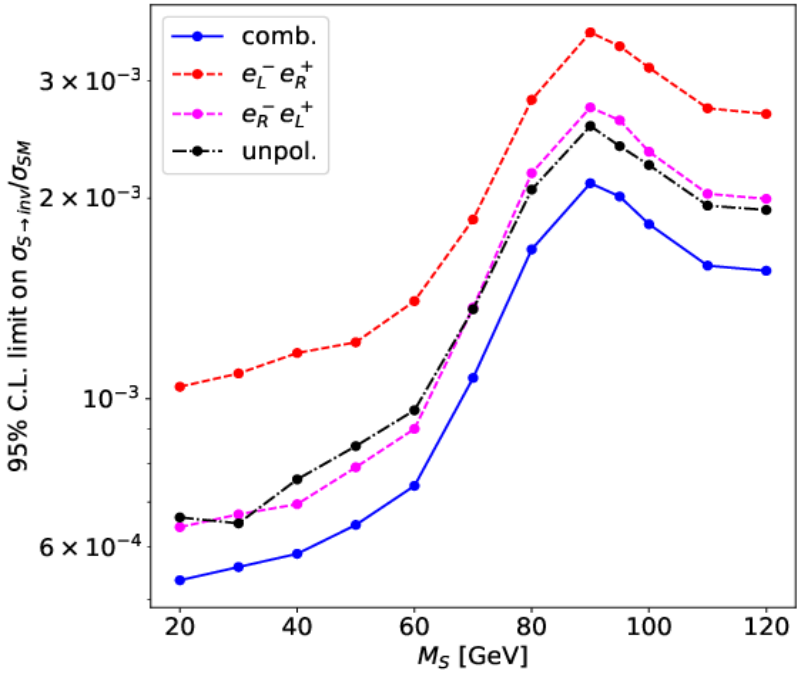
By exploring the leptonic Z decay, expected limits on the production cross section times BR(S→W^+W^-) should be comparable to those obtained in the $b\bar{b}$ channel

Searches in invisible decay channel

DM particles are introduced by many theories predicting invisible decays of Higgs-like scalars

- Study performed for 250 GeV ILC scenario
- Detector response for background and signal samples uses DELPHES fast simulation
- The study considers hadronic Z decays – highest sensitivity – and S^0 decays into invisible final states – eg. dark sector

$e^+e^- \rightarrow ZS^0 \rightarrow q\bar{q}$ invisible



Limits computed in a model-independent approach

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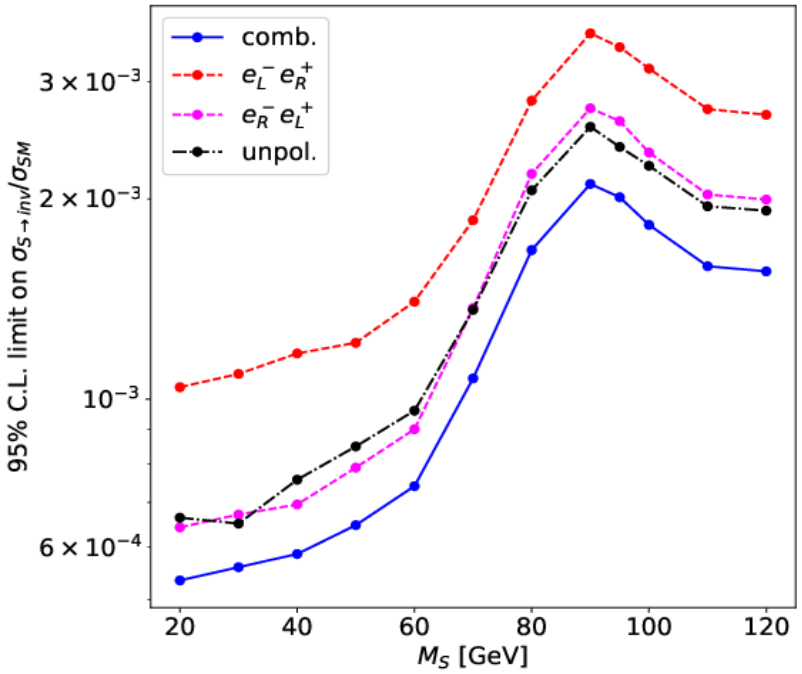
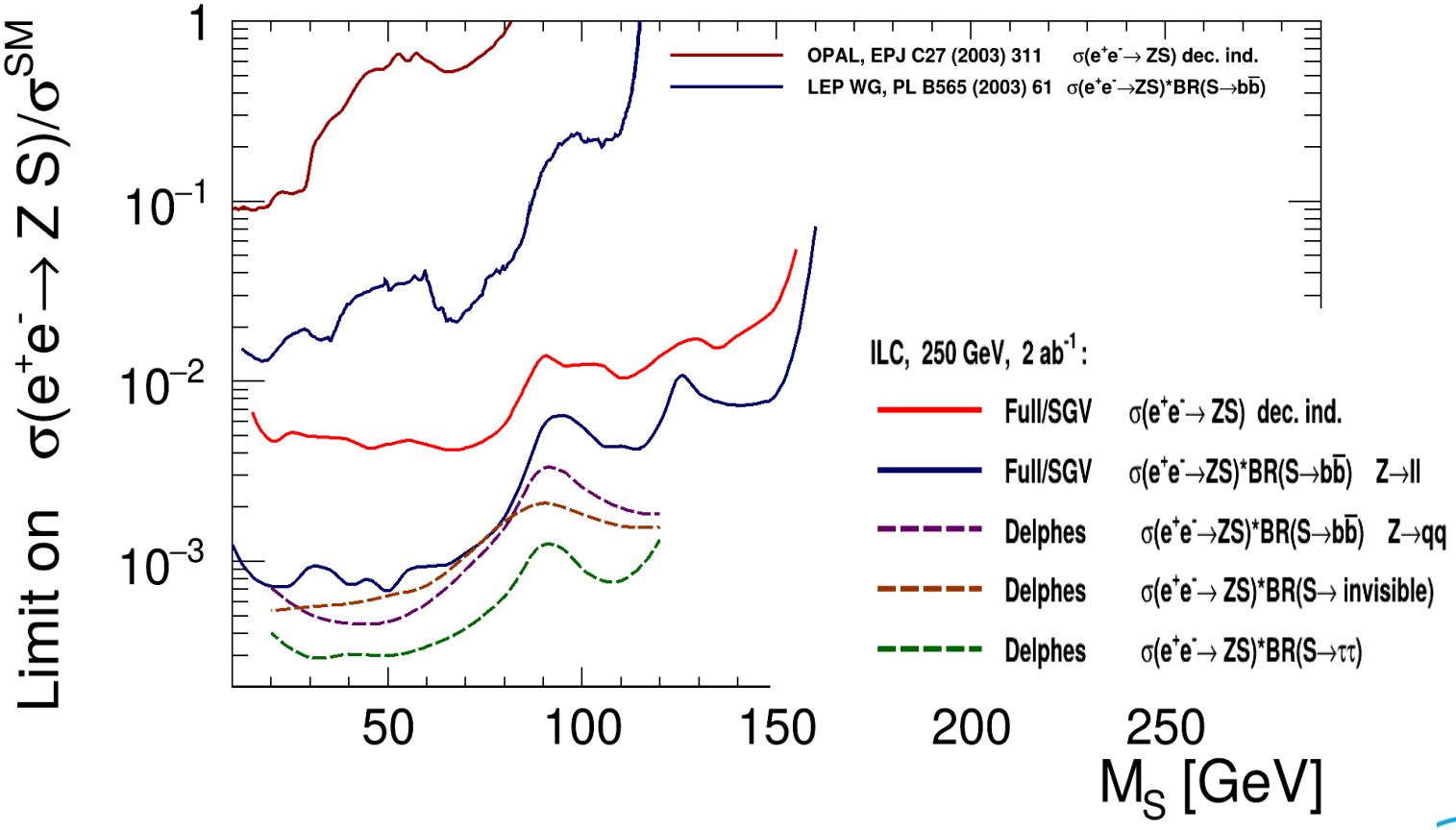
Searches in invisible decay channel (ctd.)

- $e^-_R\, e^+_L$ expected to produce significant better results than opposite polarisation, due to the suppression of the W^+W^- production, main background channel
- 900 fb^{-1} collected with the preferred polarisation configuration gives similar limits as 2 ab^{-1} with unpolarised beams



Combined analysis of the four polarisations in the H-20 running scenario results in about a 20% improvement with respect to the same luminosity for unpolarised beams

Summary of presented searches



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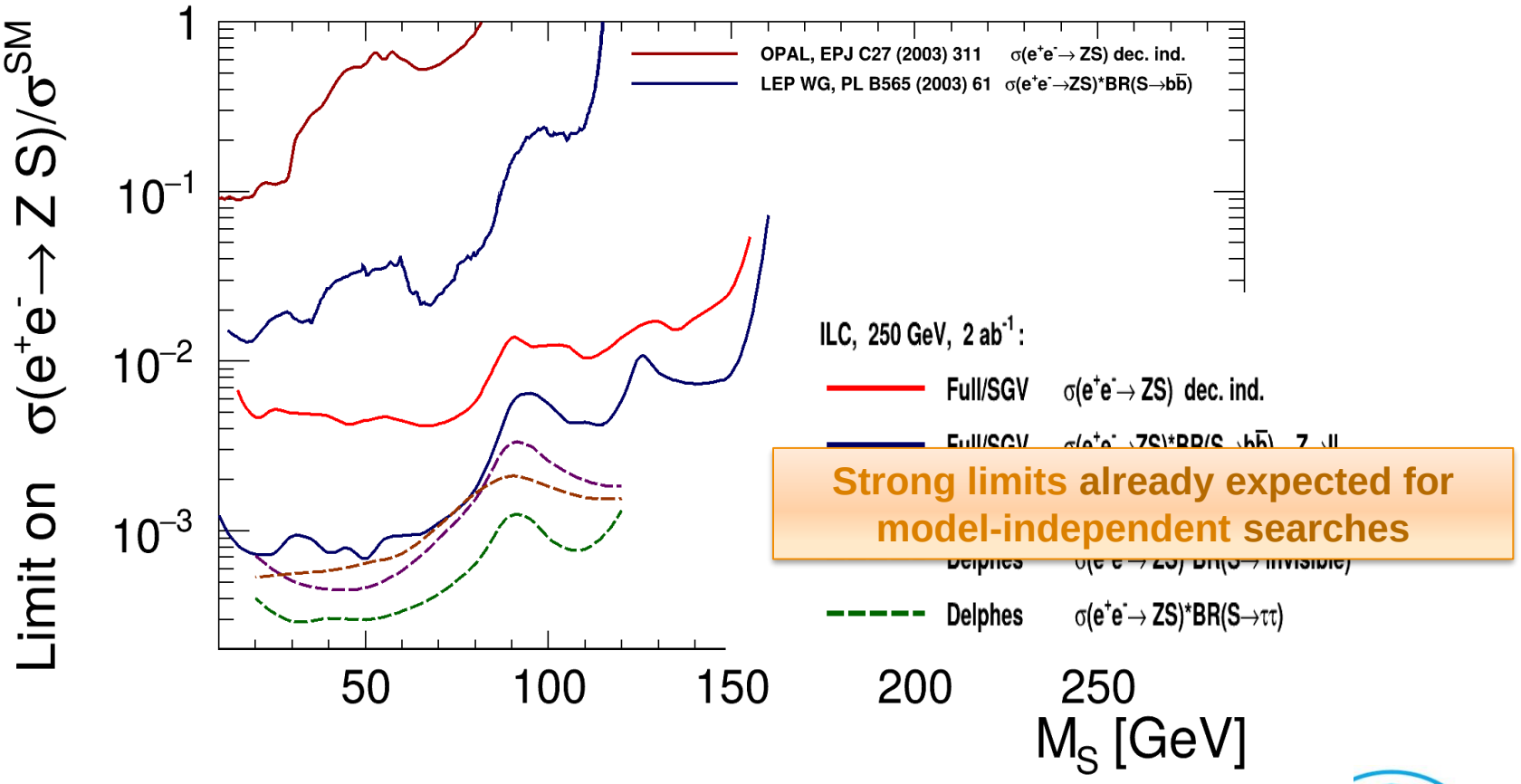

Strong limits already expected for model-independent searches

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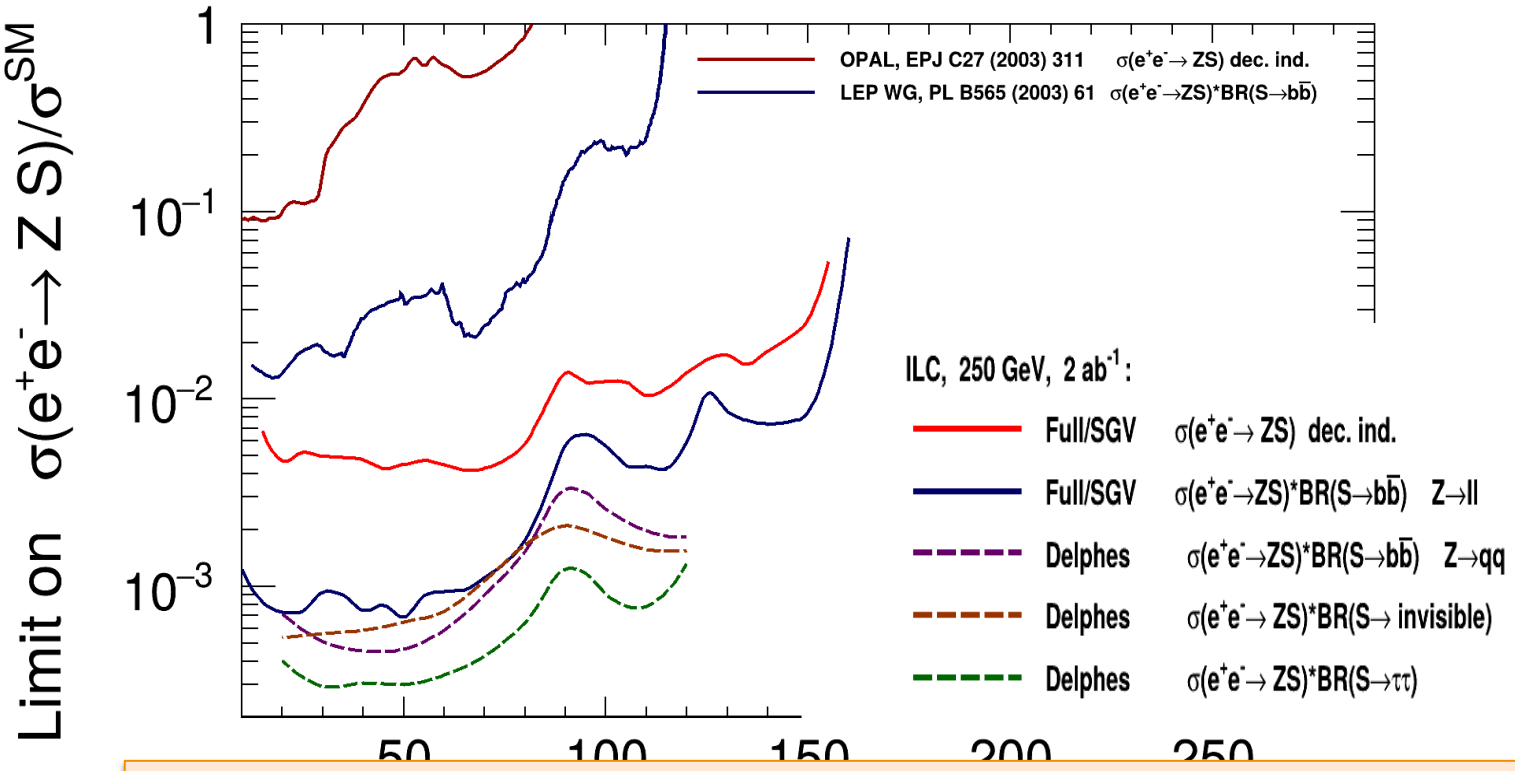
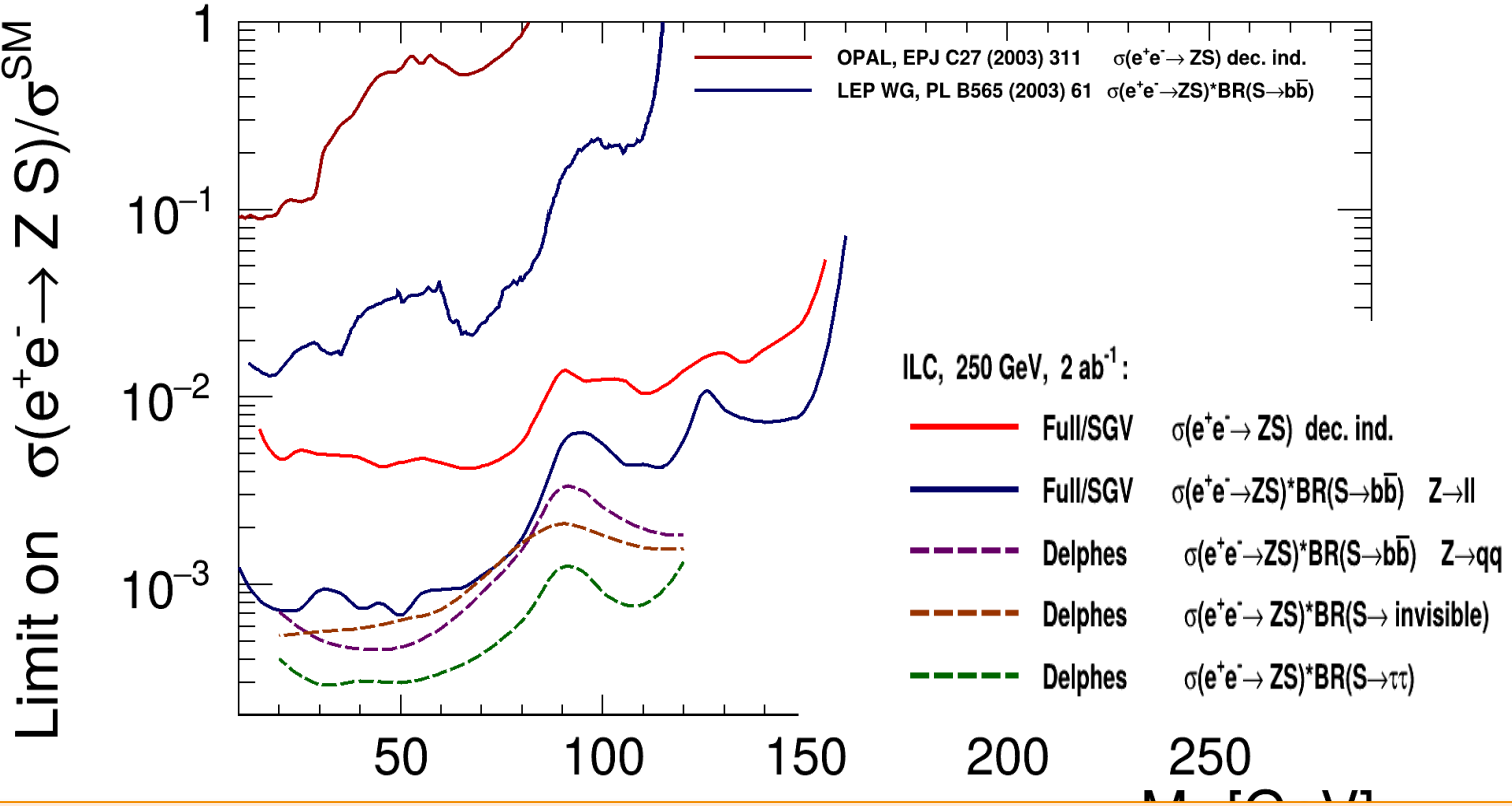
Summary of presented searches



If the light scalar preferentially decays to tau pairs, an improvement in search sensitivity by more than one order of magnitude is expected, making this channel the most sensitive one

Summary of presented searches



Searches in invisible decays and for scalar decays to $b\bar{b}$ with hadronic Z boson decays are slightly weaker due to much higher backgrounds … constraints to scalar decays to $b\bar{b}$ with a leptonic signature are limited by the leptonic branching ratio of the Z boson

Conclusions

The potential of future e^+e^- Higgs factories for searching for light exotic scalars have been proved

- BSM scenarios involving light scalars, with masses accessible at e^+e^- Higgs factories, are not excluded with the latest experimental data
- Sizable production cross sections for new scalars coincide with non-standard decay patterns … opening a range of decay channels to study
- Many light scalar exotic searches in the scalar-strahlung process have been performed