Decay-mode independent searches for new light scalars at future Higgs factories

Teresa Núñez - DESY



- Motivation
- Searches @ 250 GeV:
  - Scalar-strahlung with *Z* to *ee*/μμ
- Searches @ 550 GeV:
  - Scalar-strahlung with *Z* to *ee*/μμ
  - ZZ fusion
- Conclusions and Outlook

International Workshop on Future Linear Colliders
LCWS, 9-13 Nov 2026, KEK

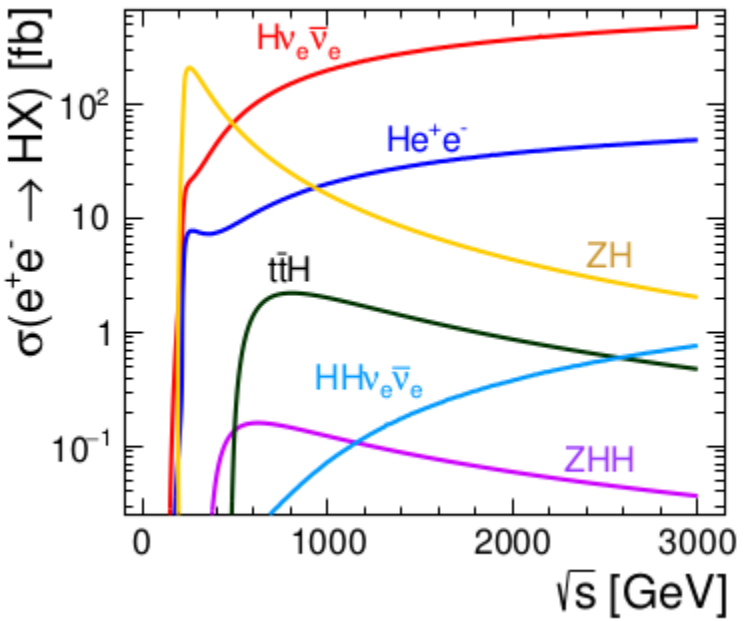
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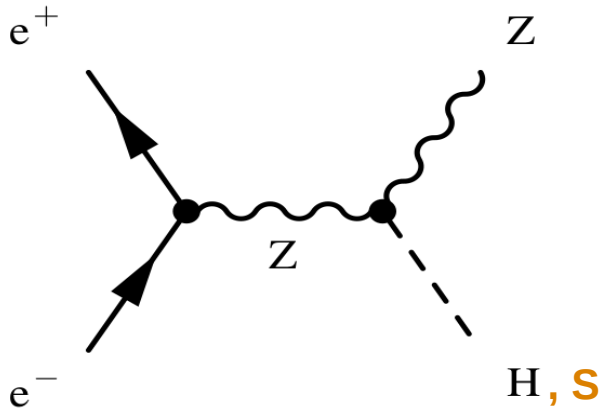
DESY.

Motivation

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



Scalar-strahlung, similar to the Higgs-strahlung, could be the dominant light extra scalar production channel for $\sqrt{s}$ below 450 GeV



Higgs-Strahlung

WW fusion

ZZ fusion

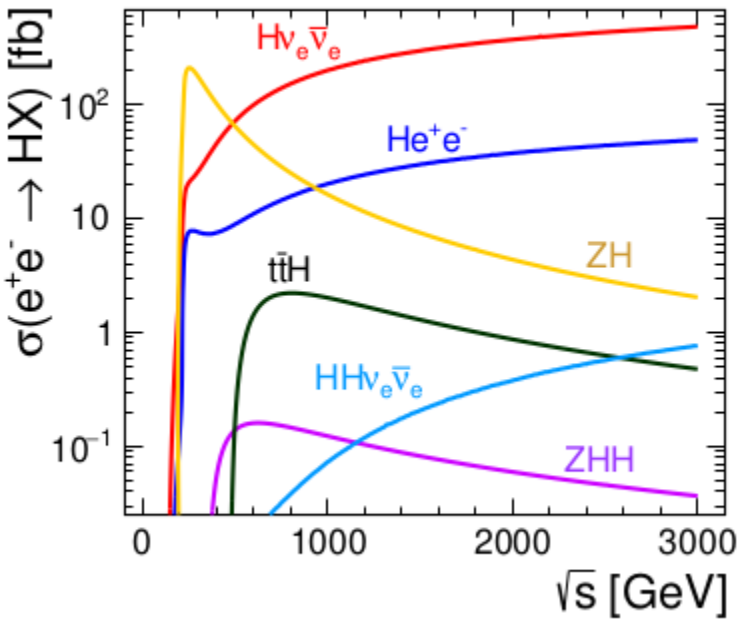
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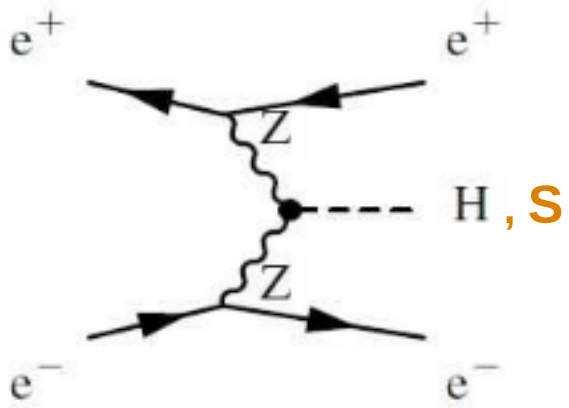
DESY.

Motivation

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



ZZ fusion, with two electrons in the final state, should be taken into account at $\sqrt{s}$ = 550 GeV



Higgs-Strahlung

WW fusion

ZZ fusion

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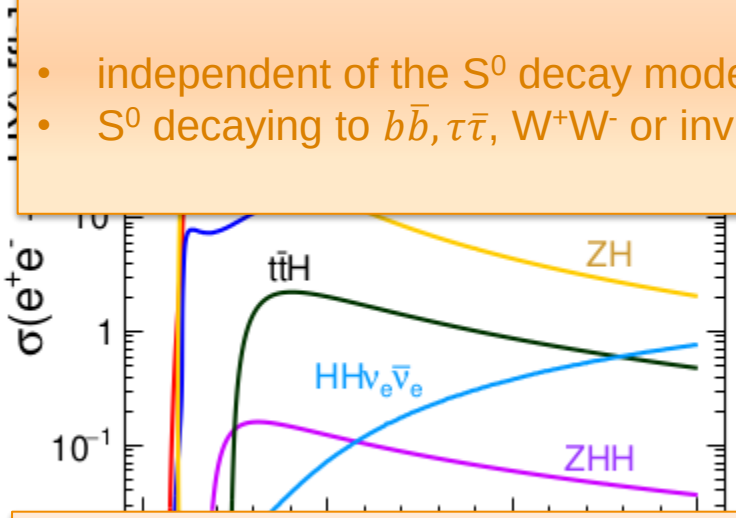
Motivation

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

Different search strategies:

- independent of the S^0 decay mode
- S^0 decaying to $b\bar{b}, \tau\bar{\tau}$, W^+W^- or invisible

…usion, with two electrons in the final state, …uld be taken into account at $\sqrt{s}$ = 550 GeV



This contribution covers the model independent searches



Model dependent search talks:

Searches for light exotic scalars in the S -> bb decay channel at future Higgs factories (B. Brudnowski)

Prospects for light exotic scalar measurements in di-tau decay channel at future Higgs factories (A.F. Zarneki)

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ZZ fusion

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Decay model independent searches

Studies based on the ILD@ILC:

- $\sqrt{s}$ = 500 GeV (previous !!!, not covered in this talk):
  - full simulation and reconstruction procedures for signal and background … but …
  - not current ILD@ILC experimental conditions
  - decays of the Z to two muons

- $\sqrt{s}$ = 250 GeV:
  - full simulation and reconstruction procedures for background, SGV fast simulation for signal
  - current ILD@ILC experimental conditions
  - S-strahlung production with decays of the Z to two muons and two electrons

- $\sqrt{s}$ = 550 GeV:
  - SGV fast simulation for detector simulation and reconstruction for background and signal samples
  - ILD@ILC 500 GeV experimental conditions (extension to different luminosity and polarisation scenarios)
  - S-strahlung production with decays of the Z to two muons and two electrons
  - ZZ fusion production

Searches @ 250 GeV

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

Searches are based on the recoil of Z against the new scalar

Independent of the S^0 decay mode

- Searches done for any mass and based on the recoil of the Z against the scalar
- Covering leptonic Z decays (clearest topology)

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

Samples:

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

Searches @ 250 GeV

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

Searches are based on the recoil of Z against the new scalar

Independent of the S^0 decay mode

- Searches done for any mass and based on the recoil of the Z against the scalar
- Covering leptonic Z decays (clearest topology)

Using the full detector simula

ILC running scenario @250 GeV:

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

Samples:

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

Event selection: Z to $\mu\mu$ channel

Use “Z-tagging” for unbiased selection of scalar production events

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

- Identification of ISR photons
- Select events without high-energetic ISR photon:
  - none or $E\gamma < 100$ GeV for $|\cos\theta| < 0.95$ or $E\gamma < 75$ GeV for $|\cos\theta| > 0.95$
- Identification of isolated muons
- Perform isolated muon pairing
- Cuts on kinematic variables (FSR corrections applied), accepted if
  - $M_{\mu+\mu-} \in [70, 110]$ GeV
  - $P^T_{\mu+\mu-} \in [0, 120]$ GeV
- Cuts on output of two BDTGs, 2f-MVA and 4f-MVA, trained against 2 fermion and 4 fermion backgrounds, respectively.
  - Input variables:: $M_{\mu+\mu-}^{FSR}$, $\cos\theta_{\mu+}^{FSR}$, $\cos\theta_{\mu-}^{FSR}$, $\cos\theta_{\mu+\mu-}^{FSR}$, $\cos\theta\mu - \mu^{FSR}$, $\pi - (\phi_{\mu+} - \phi_{\mu-})$
  - cut limits depend on scalar mass
- Limits computed based on fractional event counting using the M_{recoil} distribution

Avoid any possible dependence on the scalar decay channels (could even be exotic or invisible)

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DESY.

Event selection: Z to *ee* channel

Similar to the event selection used for the Z to two muons channel

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

- Identification of ISR photons
- Select events without high-energetic ISR photon:
  - none or $E\gamma < 100$ GeV for $|\cos\theta| < 0.95$ or $E\gamma < 75$ GeV for $|\cos\theta| > 0.95$
- Identification of isolated electrons
- Perform isolated electron pairing
- Cuts on kinematic variables (FSR corrections applied), accepted if
  - $M_{e+e-} \in [70, 110]$ GeV
  - $P^T_{e+e-} \in [0, 120]$ GeV
- Cuts on output of two BDTGs, 2f-MVA and 4f-MVA, trained against 2 fermion and 4 fermion backgrounds, respectively.
  - Input variables: M_{e+e-}^{FSR}, $\cos\theta_{e+}^{FSR}$, $\cos\theta_{e-}^{FSR}$, $\cos\theta_{e+e-}^{FSR}$, $\cos\theta e{-}e^{FSR}$, $\pi - (\phi_{e+} - \phi_{e-})$
  - cut limits depend on scalar mass
- Select events with less than 50 GeV ISR energy
- Limits computed based on fractional event counting using the M_{recoil} distribution

Add cut in ISR energy

Additional cut based on ISR energy due to large Bhabha background

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DESY.

Cut flow: $\mu^+\mu^-$ vs e^+e^-

Scalar mass 50 GeV

P(e-,e+)=(-80%,+30%)

$\mu\mu$

	Signal	mumuHiggs	4f leptonic	4f semileptonic	2f leptonic ($\mu\mu+\tau\tau$)	Bhabha	Others	Total background	Significance
Total	25673.8	92.7e+02	22.1e+05	16.8e+06	11.7e+06	17.6e+07	13.9e+07	34.6e+07	
After full selection	8680.1	20.7	30.5e+02	26.3e+02	15.2e+03	0	0	30.9e+03	50.5

ee

	Signal	eeHiggs	4f leptonic	4f semileptonic	2f leptonic (mumu+tautau)	Bhabha	Others	Total background	Significance
Total	30288.7	98.7e+02	22.1e+05	16.8e+06	11.7e+06	17.6e+07	13.9e+07	34.6e+07	
After full selection	17088.7	40.9e+02	54.1e+01	19.0e+02	11.2	24.7e+03	0	31.2e+03	77.7

Scalar mass 120 GeV

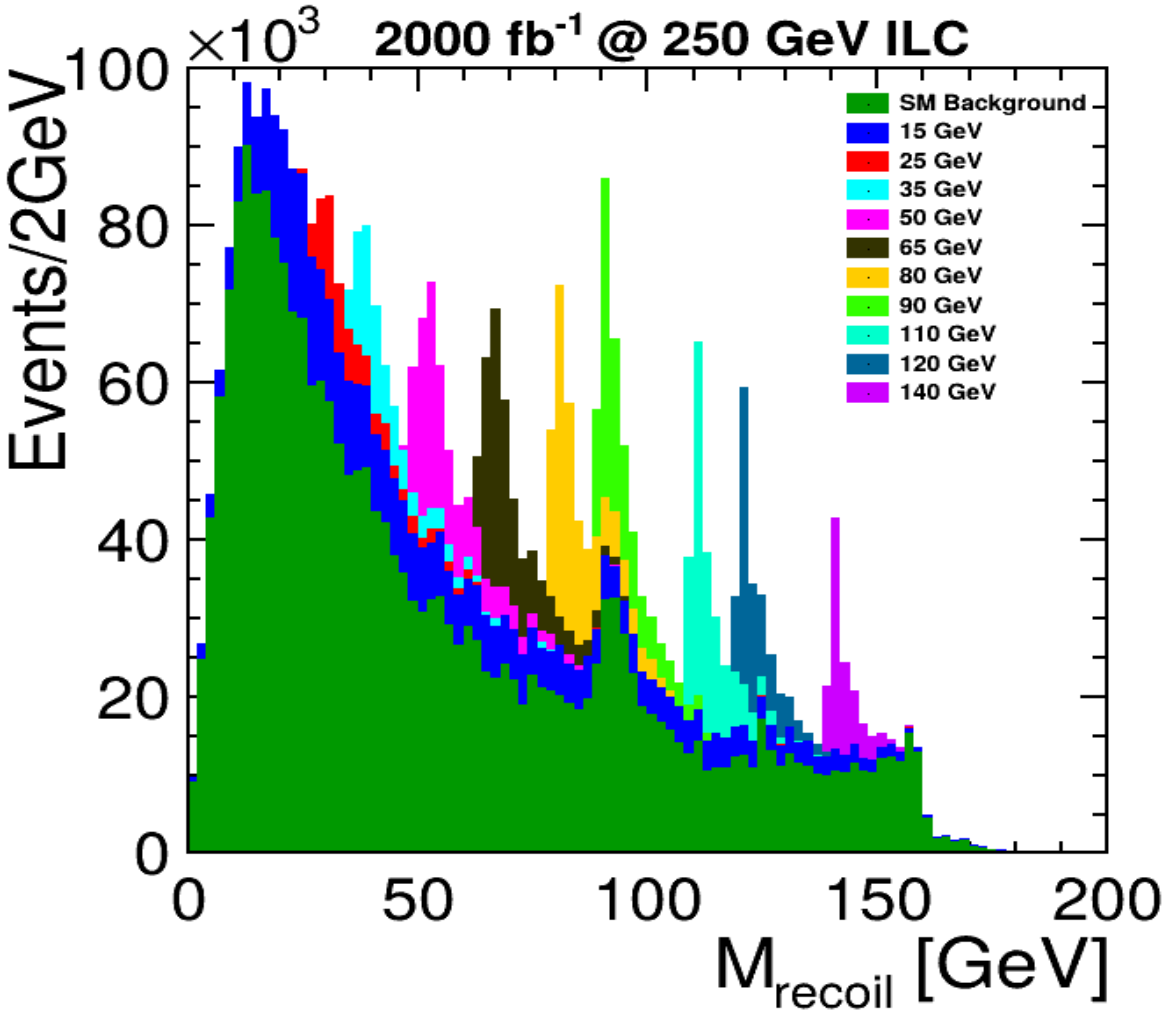
$\mu\mu$

	Signal	mumuHiggs	4f leptonic	4f semileptonic	2f leptonic ($\mu\mu+\tau\tau$)	Bhabha	Others	Total background	Significance
Total	10437.4	92.7e+02	22.1e+05	16.8e+06	11.7e+06	17.6e+07	13.9e+07	34.6e+07	
After full selection	6156.26	54.7e+02	16.7e+03	19.2e+03	20.5e+03	0	0	62.0e+03	23.6

ee

	Signal	eeHiggs	4f leptonic	4f semileptonic	2f leptonic (mumu+tautau)	Bhabha	Others	Total background	Significance
Total	11186.5	92.7e+02	22.1e+05	16.8e+06	11.7e+06	17.6e+07	13.9e+07	34.6e+07	
After full selection	7156.87	56.8e+02	76.8e+01	18.4e+02	22.4	30.1e+03	0	38.4e+03	33.5

Recoil mass spectrum: signal vs background

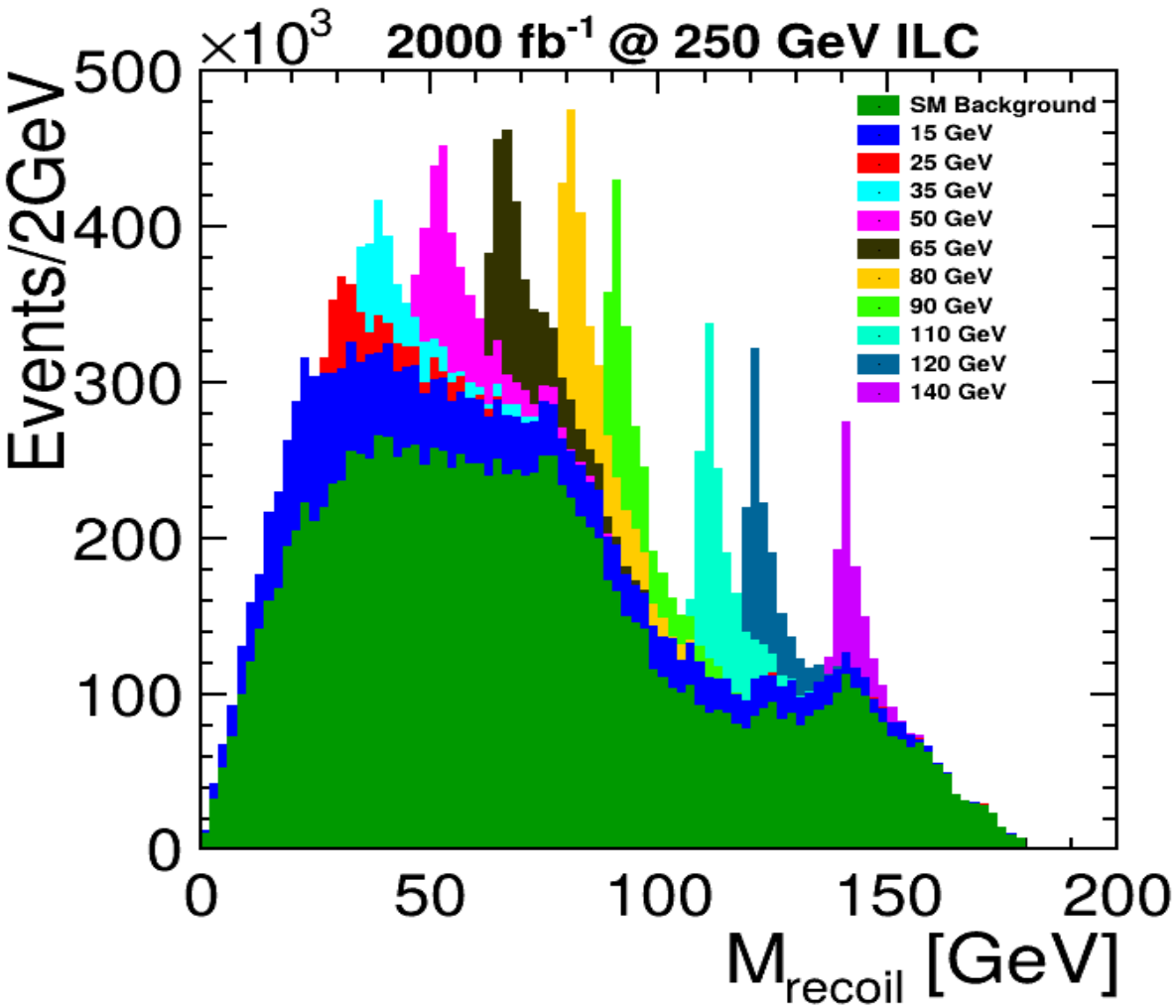


$e^+e^- \rightarrow ZS^0 \rightarrow \mu^+\mu^- S^0$

Before cuts on the MVA output

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

Recoil mass spectrum: signal vs background

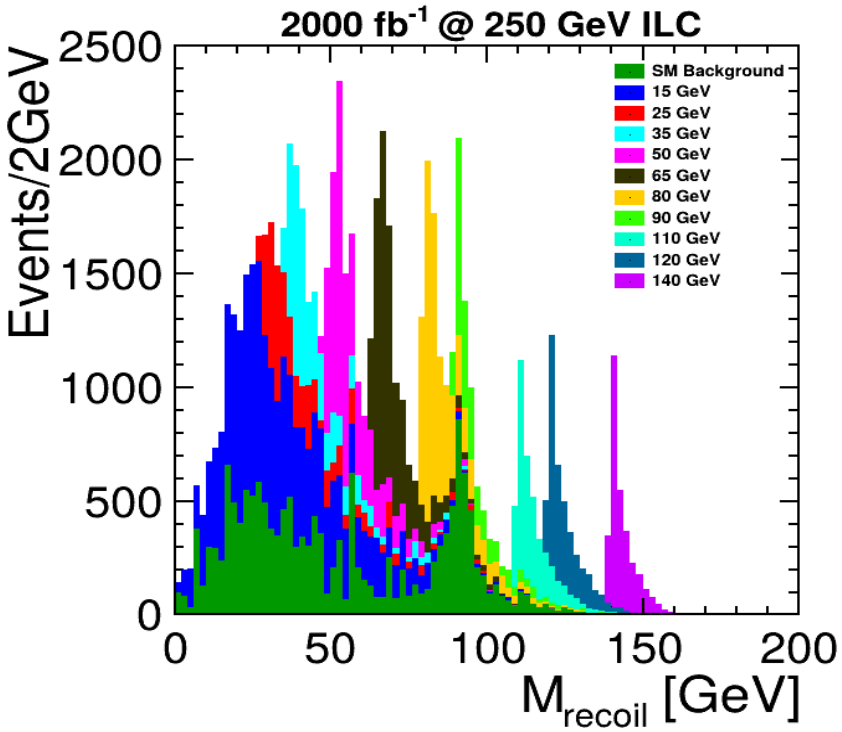


$e^+e^- \rightarrow ZS^0 \rightarrow e^+e^-S^0$

Before cuts on the MVA output

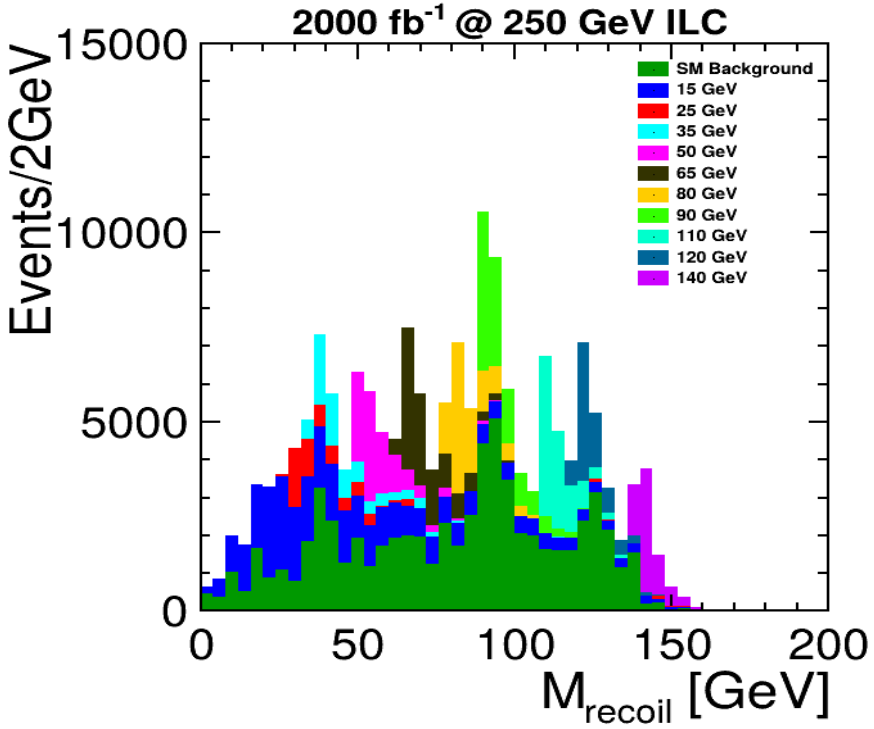
$$M^2_{rec} = (\sqrt{s} - E_{ll})^2 - \left|\vec{P}_{ll}\right|^2$$

Recoil mass spectrum: signal vs background



After all cuts

(Background for scalar mass 50 GeV)

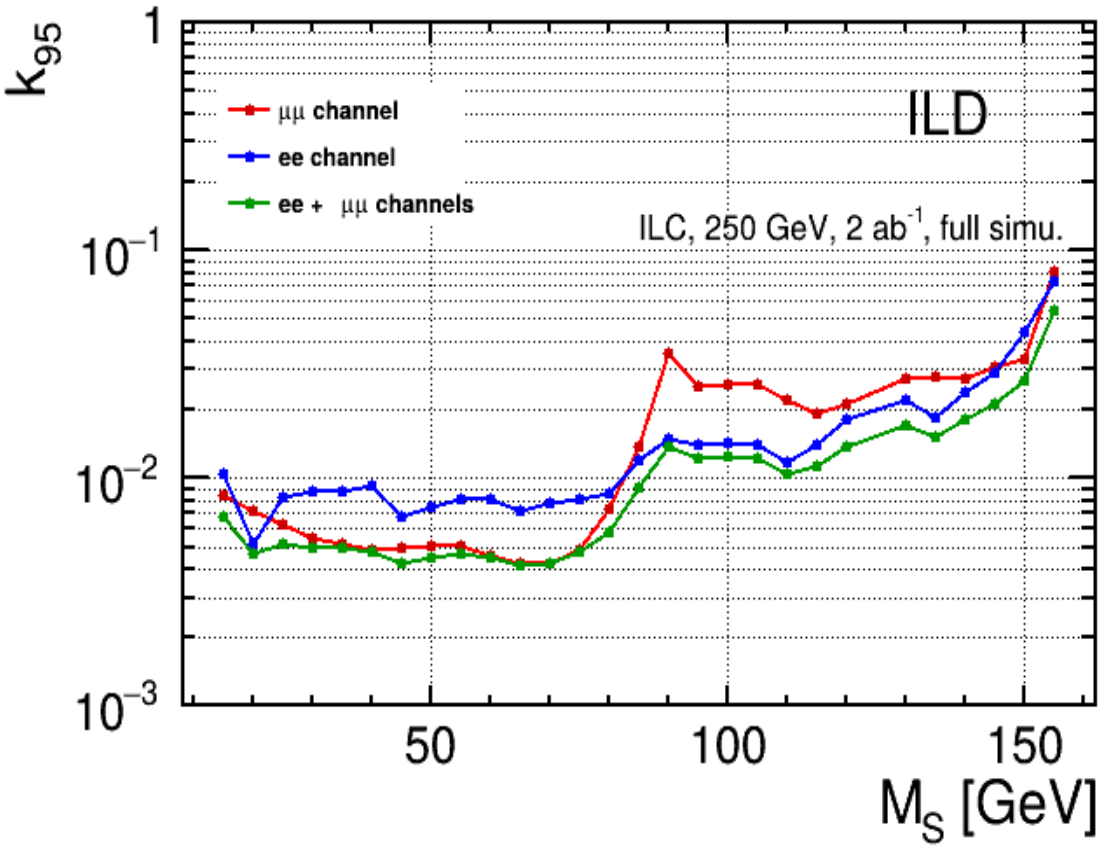


$e^+e^- \rightarrow ZS^0 \rightarrow \mu^+\mu^- S^0$

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

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

Scalar search sensitivity @ 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

Less sensitivity of Z to electron decay channel for smaller masses due to contribution of bhabha background

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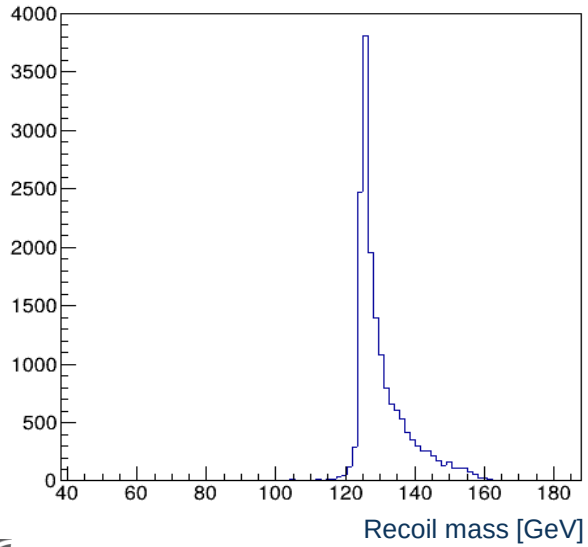
Check independency on S decay modes

No dependency on the decay mode, except if gammas are implied

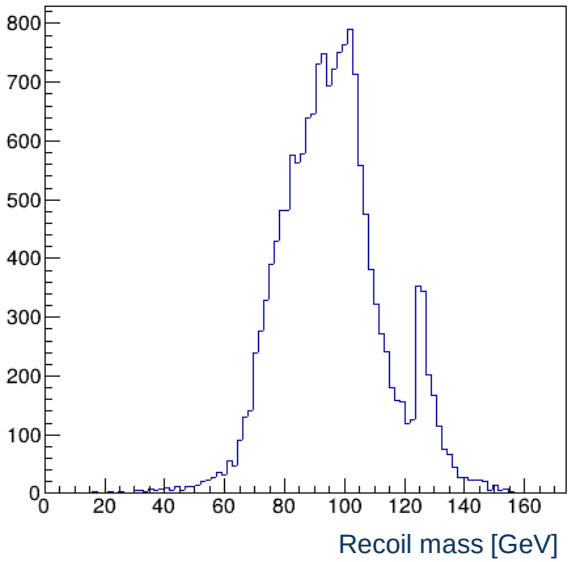
S → $\gamma\gamma$ and S → Z γ suffer from the cut on ISR energy. The ISR correction in the recoil mass can not be done in the same way, since the highest ISR photon may come from the S decay.

Not effect in the rest of the cuts, which depend only on the kinematics of the Z boson. Effect in the ISR energy cut observable for high scalar mass (> ~ 135 GeV)

Recoil mass



Recoil mass ISR corrected



S → Z γ decay

SM Higgs full simulation

Extending searches @ 550 GeV

As an example, the Linear Collider Facility (LCF) recently proposed at CERN assumes major runs at 250 and 550 GeV … make interesting …

Extension of the searches to $\sqrt{s}$ = 550 GeV

Even if for the LCF higher integrated luminosities and twice higher degree of positron polarisations are proposed …

Studies based on the ILD@ILC with 500 GeV experimental conditions (same luminosities and degree of polarisations)

Extending searches @ 550 GeV

Analysis details:

- SGV fast simulation for detector simulation and reconstruction for background and signal samples
- S-Strahlung production with Z leptonic decays (two muons/two electrons):

  - same analysis flow as for the previous analysis at $\sqrt{s}$ = 250 GeV
- ZZ-fusion production

ILD@ILC 550 GeV assuming the standard 500 GeV running scenario:

- P(e-,e+)=(-80%,+30%) 1.6ab^{-1}, P(e-,e+)=(+80%,-30%) 1.6ab^{-1}
- P(e-,e+)=(-80%,-30%) 0.4ab^{-1}, P(e-,e+)=(+80%,+30%) 0.4ab^{-1}

S-Strahlung: Z to $\mu\mu$ channel

Use “Z-tagging” for unbiased selection of scalar production events

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

- Identification of ISR photons
- Select events without high-energetic ISR photon:
  - none or Eγ less than a limit depending on the scalar mass ([200, 60] GeV)
- Identification of isolated muons
- Perform isolated muon pairing
- Cuts on kinematic variables (FSR corrections applied), accepted if
  - $M_{\mu+\mu-} \in$ [70, 110] GeV
  - $P^T_{\mu+\mu-} \in$ [0, 270] GeV

Adjusted kinematic cuts from $\sqrt{s}$ = 250 GeV to $\sqrt{s}$ = 550 GeV

- Cuts on output of two BDTGs, 2f-MTVA and 4f-MTVA, trained against 2 fermion and 4 fermion backgrounds, respectively.
  - Input variables:: $M_{\mu+\mu-}^{FSR}$, $\cos\theta_{\mu+}^{FSR}$, $\cos\theta_{\mu-}^{FSR}$, $\cos\theta_{\mu+\mu-}^{FSR}$, $\cos\theta\mu - \mu^{FSR}$, $\pi - (\phi_{\mu+} - \phi_{\mu-})$
  - training done for each scalar mass separately
  - cut limits depends on scalar mass
- Limits computed based on fractional event counting using the M_{recoil} distribution

Avoid any possible dependence on the scalar decay channels (could even be exotic or invisible)

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S-Strahlung: Z to ee channel

Use “Z-tagging” for unbiased selection of scalar production events

Same cut flow as the one used for the previous studies

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

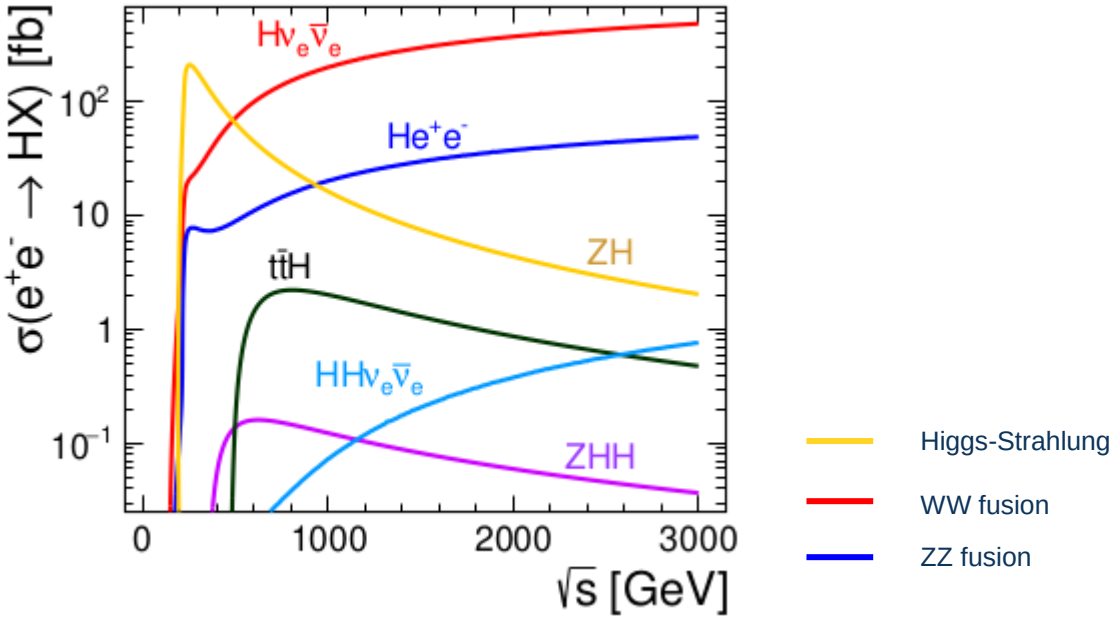
- Identification of ISR photons
- Select events without high-energetic ISR photon:
  - none or $E\gamma$ less than a limit depending on the scalar mass ([200, 60] GeV)
- Identification of isolated leptons
- Perform isolated lepton pairing
- Cuts on kinematic variables (FSR corrections applied), accepted if
  - $M_{e+e-} \in [70, 110]$ GeV
  - $P^T_{e+e-} \in [0, 270]$ GeV
- Cuts on output of two BDTGs, 2f-MTVA and 4f-MTVA, trained against 2 fermion and 4 fermion backgrounds, respectively.
  - Input variables: M_{e+e-}^{FSR}, $\cos\theta_{e+}^{FSR}$, $\cos\theta_{e-}^{FSR}$, $\cos\theta_{e+e-}^{FSR}$, $\cos\theta e{-}e^{FSR}$, $\pi - (\phi_{e+} - \phi_{e-})$
  - training done for each scalar mass separately
  - same limits used for all scalar masses
- Select events with less than 50 GeV ISR energy
- Limits computed based on fractional event counting using the M_{recoil} distribution (with ISR correction)

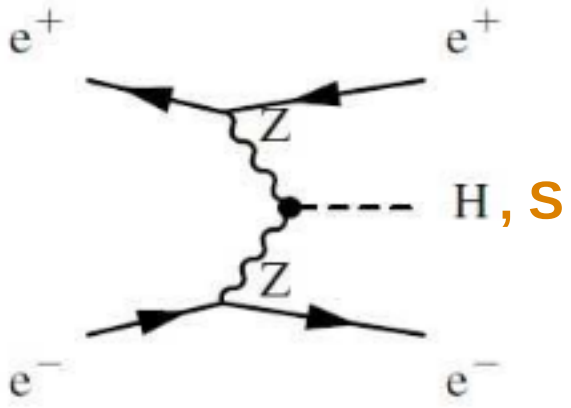
Adjusted kinematic cuts from $\sqrt{s}$ = 250 GeV to $\sqrt{s}$ = 550 GeV

Avoid any possible dependence on the scalar decay channels (could even be exotic or invisible)

ZZ fusion production

Model independent searches based on the recoil of the scalar against the Z mostly exclude extra scalar production by other processes that could be relevant at higher $\sqrt{s}$ values





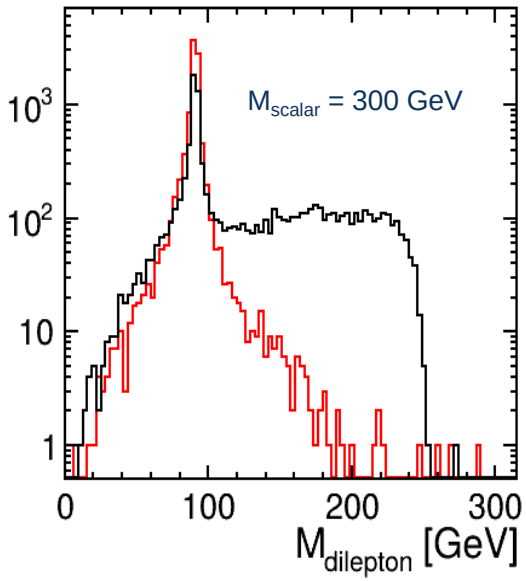
Higgs-Strahlung

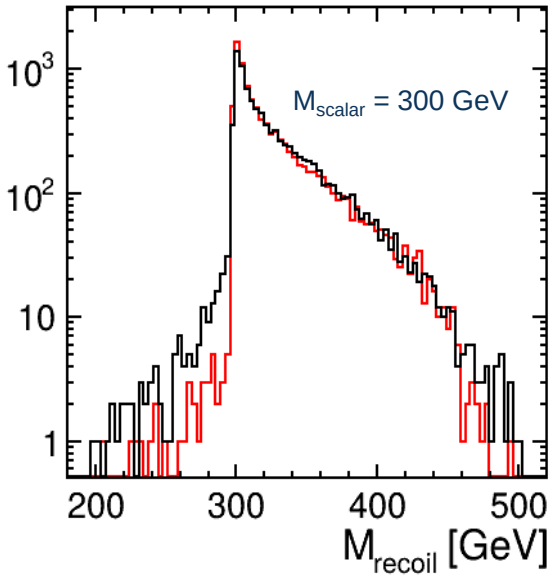
WW fusion

ZZ fusion

ZZ fusion, with two electrons in the final state, should be taken into account at $\sqrt{s}$ = 550 GeV when analyzing the samples with an extra scalar and two electrons in the final state (same final state as for the S-Strahlung production with Z decaying to electrons)

How profit from the ZZ fusion production?





Z to electron pair

Z to muon pair

Remove Z constraints in searches at 550 GeV with two electrons in the final state

Keep the search based on recoil of the new scalar against the two electrons in the final state

From S-strahlung to ZZ fusion event selection

~~Use "Z-tagging" for unbiased selection of scalar production events~~

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

- Identification of ISR photons
- Select events without high-energetic ISR photon:
  - none or $E\gamma$ less than a limit depending on the scalar mass ([200, 60] GeV)
- Identification of isolated leptons
- Perform isolated lepton pairing
- Cuts on ~~kinematic variables~~ (FSR corrections ~~applied~~), accepted if
  - $M_{e^+e^-} \in [70, 110]$ GeV
  - $P^T_{e^+e^-} \in [0, 270]$ GeV
- Cuts on output of two BDTGs, 2f-MTVA and 4f-MTVA, trained against 2 fermion and 4 fermion backgrounds, respectively.
  - Input variables: ~~$M_{e^+e^-}^{FSR}$~~, $\cos\theta_{e^+}^{FSR}$, $\cos\theta_{e^-}^{FSR}$, $\cos\theta_{e^+e^-}^{FSR}$, $\cos\theta e{-}e^{FSR}$, $\pi - (\phi_{e^+} - \phi_{e^-})$
  - training done for each scalar mass separately
  - same limits used for all scalar masses
- Select events with less than 50 GeV ISR energy
- Limits computed based on fractional event counting using the M_{recoil} distribution (with ISR correction)

Avoid any possible dependence on the scalar decay channels (could even be exotic or invisible)

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Event selection: Z to $e^+ e^-$ channel

~~Use "Z-tagging" for unbiased selection of scalar production events~~

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

- Identification of ISR photons
- Select events without high-energetic ISR photon:
  - none or $E\gamma$ less than a limit depending on the scalar mass ([200, 60] GeV)
- Identification of isolated leptons
- Perform isolated lepton pairing
- Cuts on ~~kinematic variables~~ (FSR corrections applied), accepted if
  - $M_{e+e-} \in [70, 110]$ GeV
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- Se
- Limits computed based on fractional event counting using the M_{recoil} distribution (with ISR correction)

ZZ fusion events are killed by the cut in MVA training output

Kinematics ZZ fusion production is closer to background events than to signal

Avoid any possible dependence on the scalar decay channels (could even be exotic or invisible)

Event selection with ZZ fusion preselection

Not constraints in Z

Same cut flow as the one used for the previous studies, but …

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

- Identification of ISR photons
- Select events without high-energetic ISR photon:
  - none or $E\gamma$ less than a limit depending on the scalar mass ([200, 60] GeV)
- Identification of isolated leptons
- Perform isolated lepton pairing
- Cuts on kinematic variables, accepted if
  - $M_{e+e-} > 130$ GeV

… selecting ZZ fusion events, and redo the training with those events

- Cuts on output of two BDTGs, 2f-MTVA and 4f-MTVA, trained against 2 fermion and 4 fermion backgrounds, respectively.
  - Input variables: $\cos\theta_{e+}^{FSR}$, $\cos\theta_{e-}^{FSR}$, $\cos\theta_{e+e-}^{FSR}$, $\cos\theta e{-}e^{FSR}$, $\pi - (\phi_{e+} - \phi_{e-})$
  - training done for each scalar mass separately
  - same limits used for all scalar masses

… removing dilepton mass from training

- Select events with less than 50 GeV ISR energy
- Limits computed based on fractional event counting using the M_{recoil} distribution (with ISR correction)

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Event flow selecting ZZ fusion events

Scalar mass 70 GeV

Polarisation LR

	Signal	4f leptonic	4f semileptonic	2f leptonic	BhaBha	Others	Total background	Significance
Total	29852.2	1.3e+07	4.4e+06	4.5e+06	1.7e+08	6936.7	1.9e+08	0
ISR veto	28170.4	8.1e+06	2.7e+06	3.6e+06	1.2e+08	6932.1	1.4e+08	2.41
Dielectron request	19448.1	482707	276582	9890.4	5.5e+07	3.1	5.6e+07	2.60
MVA 2f	13912.7	189601	146642	91.5	1.3e+06	1.5	1.6e+06	10.76
MVA 4f	11451.7	52829.9	62970.9	2.0	1.1e+06	1.5	1.2e+06	10.30
ISR cut	10902.6	31740.8	53421.2	0	54467.6	1.5	139631	28.10

Scalar mass 350 GeV

Polarisation LR

	Signal	4f leptonic	4f semileptonic	2f leptonic	BhaBha	Others	Total background	Significance
Total	1926.4	1.3e+07	4.4e+06	4.5e+06	1.7e+08	6936.7	1.9e+08	0
ISR veto	1902.1	6.8e+06	2.3e+06	3.5e+06	1.2e+08	6854.1	1.3e+08	0.17
Dielectron request	543.0	364141	266137	9748.1	5.2e+07	3.1	5.2e+07	0.08
MVA 2f	425.6	78907.3	134217	2.0	199454	1.5	412581	0.66
MVA 4f	368.0	29245.9	61046.7	0	153706	1.5	244000	0.74
ISR cut	365.4	24677.1	57365.1	0	2649.7	1.5	84693.5	1.25

“Dielectron request” selects ZZ fusion events asking for dielectron invariant mass above 130 GeV

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DESY.

Event flow selecting ZZ fusion events

Scalar mass 70 GeV

Polarisation LR

	Signal	4f leptonic	4f semileptonic	2f leptonic	BhaBha	Others	Total background	Significance
Total	29852.2	1.3e+07	4.4e+06	4.5e+06	1.7e+08	6936.7	1.9e+08	0
ISR veto	28170.4	8.1e+06	2.7e+06	3.6e+06	1.2e+08	6932.1	1.4e+08	2.41
Dielectron request	19448.1	482707	276582	9890.4	5.5e+07	3.1	5.6e+07	2.60
MVA 2f	13912.7	189601	146642	91.5	1.3e+06	1.5	1.6e+06	10.76
MVA 4f	11451.7	52829.9	62970.9	2.0	1.1e+06	1.5	1.2e+06	10.30
ISR cut	10902.6	31740.8	53421.2	0	54467.6	1.5	139631	28.10

For higher scalar masses the cross section is smaller and ZZ fusion contributes less to production, hence very small significance

Scalar mass 350 GeV

Polarisation LR

	Signal	4f leptonic	4f semileptonic	2f leptonic	BhaBha	Others	Total background	Significance
Total	1926.4	1.3e+07	4.4e+06	4.5e+06	1.7e+08	6936.7	1.9e+08	0
ISR veto	1902.1	6.8e+06	2.3e+06	3.5e+06	1.2e+08	6854.1	1.3e+08	0.17
Dielectron request	543.0	364141	266137	9748.1	5.2e+07	3.1	5.2e+07	0.08
MVA 2f	425.6	78907.3	134217	2.0	199454	1.5	412581	0.66
MVA 4f	368.0	29245.9	61046.7	0	153706	1.5	244000	0.74
ISR cut	365.4	24677.1	57365.1	0	2649.7	1.5	84693.5	1.25

"Dielectron request" selects ZZ fusion events asking for dielectron invariant mass above 130 GeV

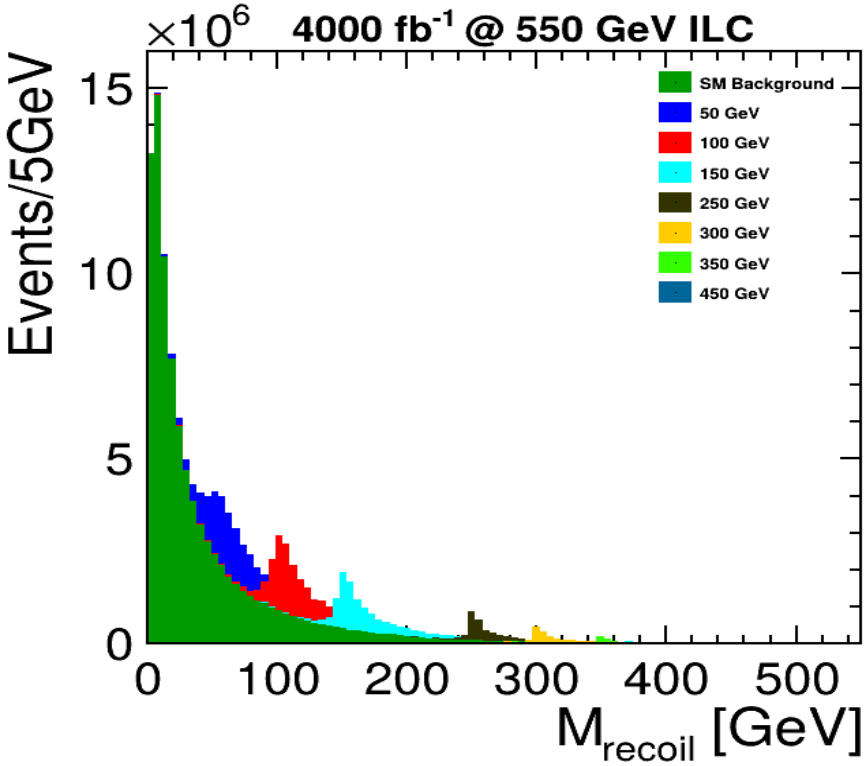
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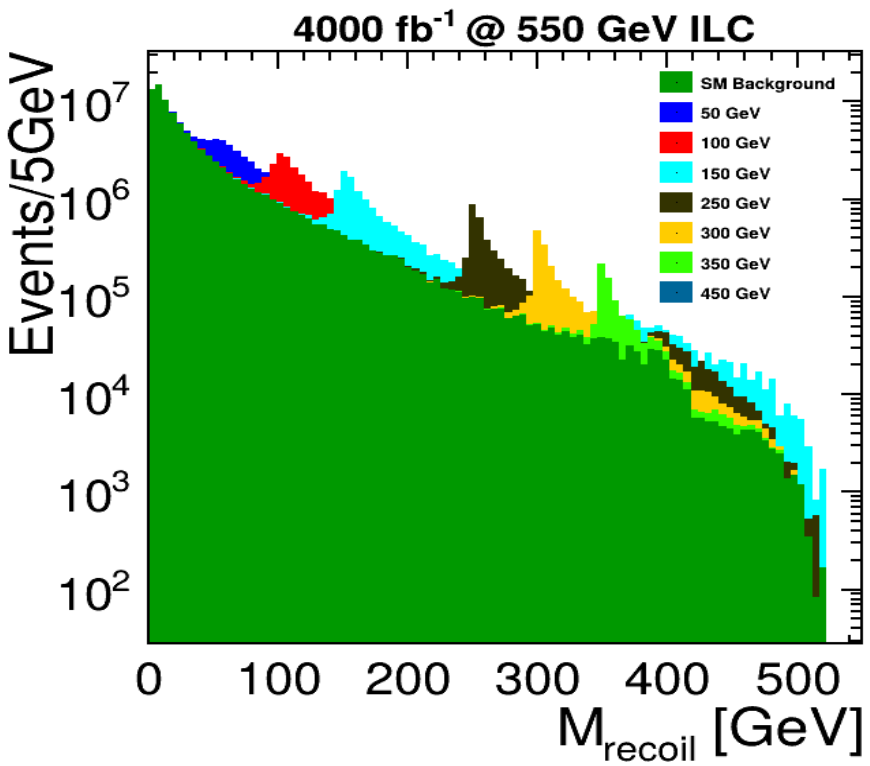
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DESY.

Recoil mass distributions selecting ZZ fusion events

Before MVA cuts



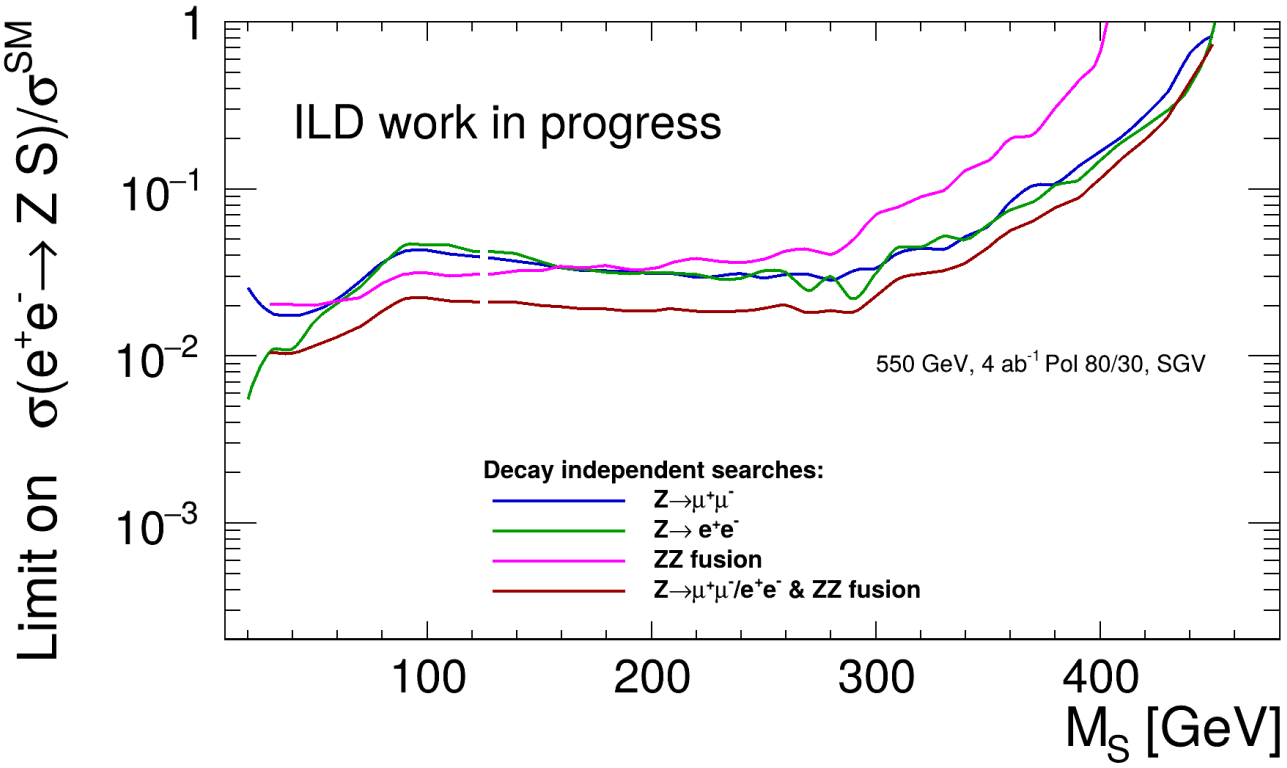


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DESY.

Limits @ 550 GeV

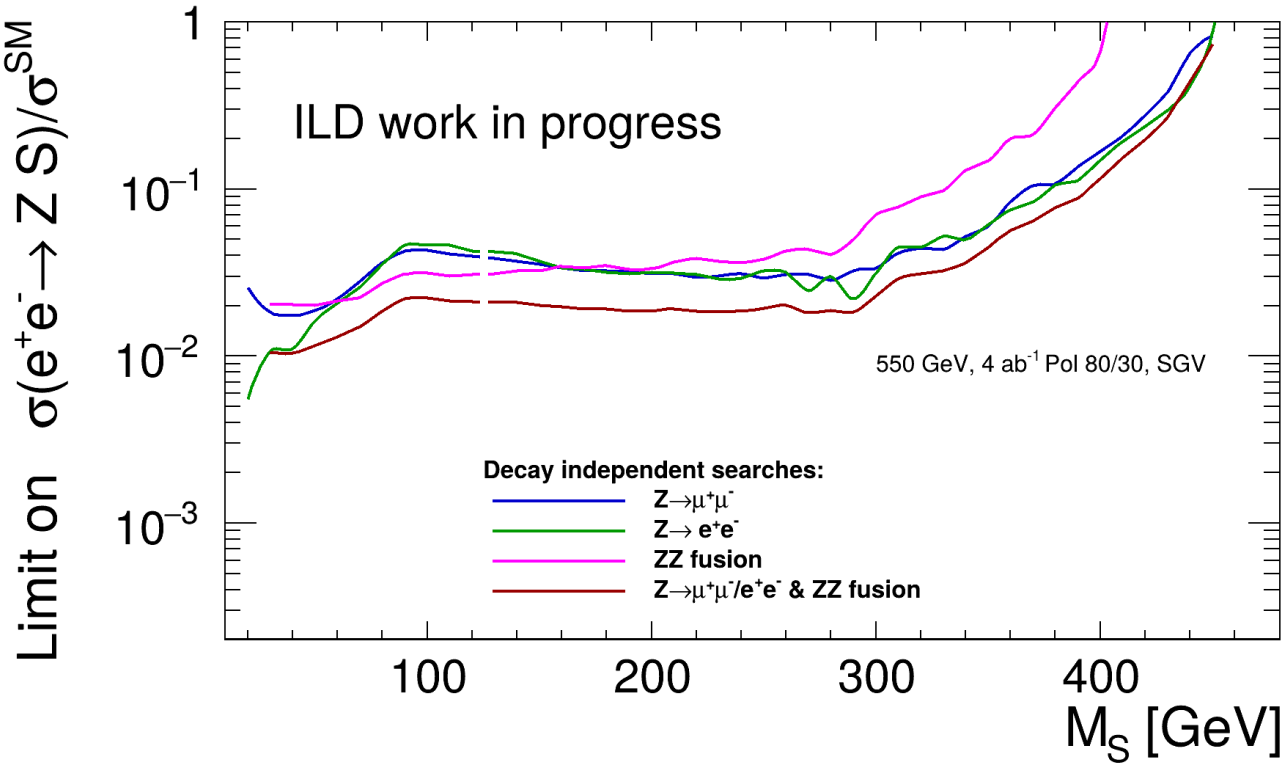


Scalar production cross section relative to SM Higgs boson production cross section at given mass

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

Channels combined using likelihood ratio statistics applied to each bin used by the fractional event counting

Limits @ 550 GeV



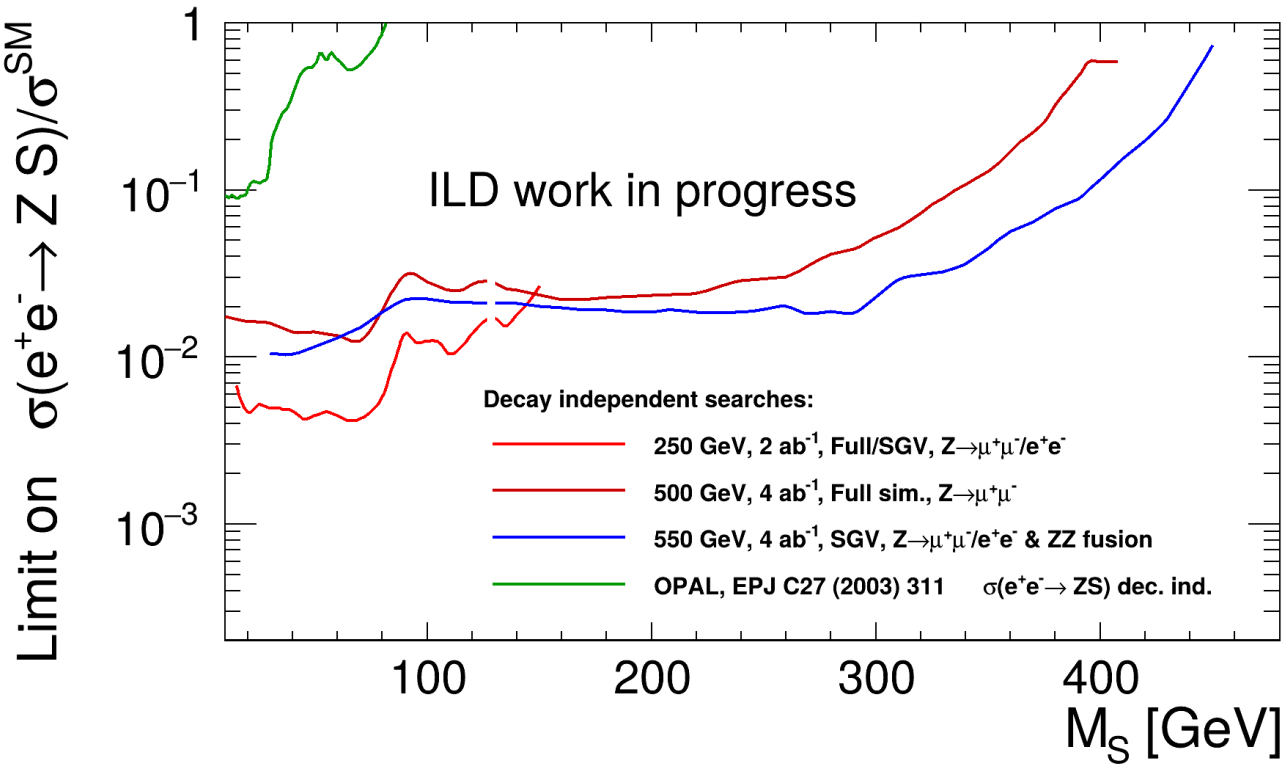
Scalar production cross section relative to SM Higgs boson production cross section at given mass

Similar sensitivity for electron and muon Z decay channels
ZZ fusion less sensitivity at higher masses (smaller contribution to production)

event counting

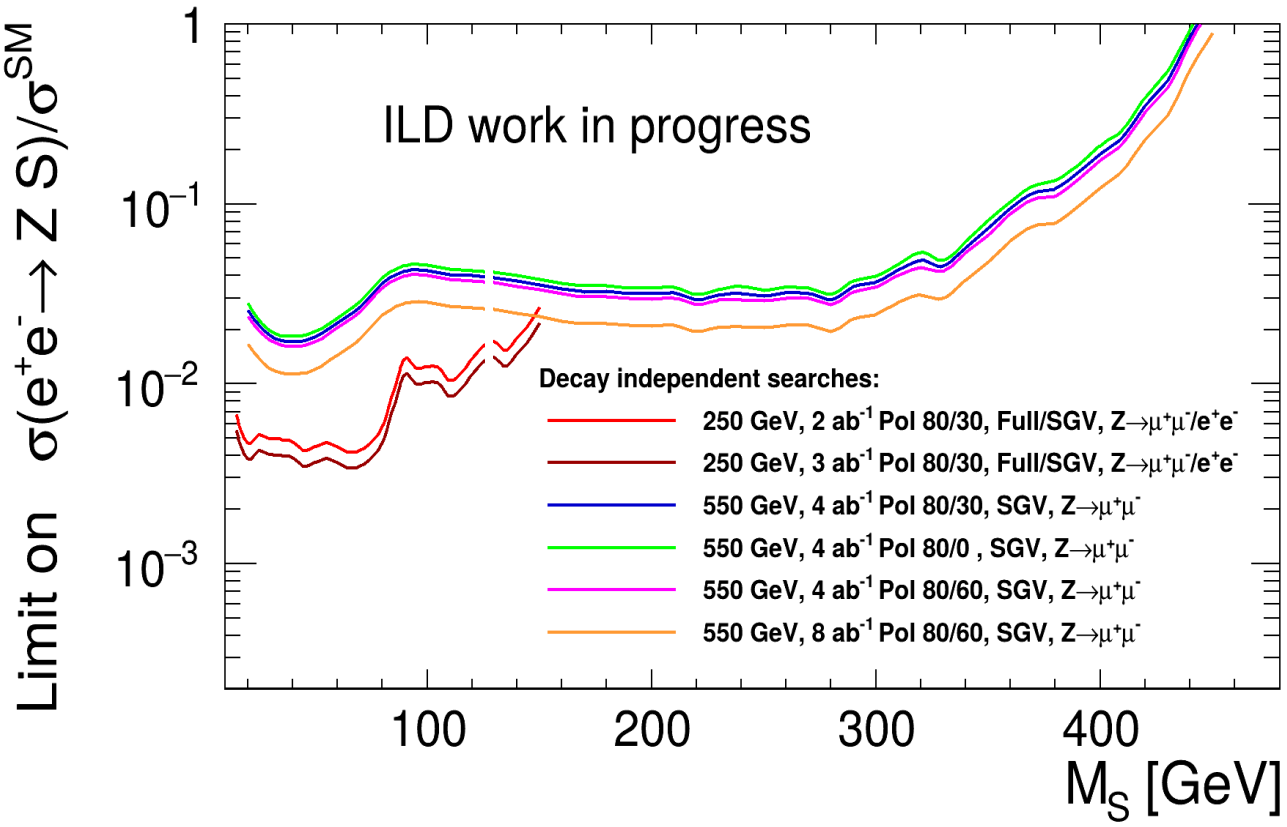
ratio statistics applied to each bin
used by the fractional event counting

Decay model independent limits



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

Changing scenario: effect of luminosity and polarisation



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

Channels combined using likelihood ratio statistics applied to each bin used by the fractional event counting

Conclusions and Outlook

- New scalars model independent searches @250 GeV and @550 GeV, based on newest MC production and ILD software, have be performed covering S-strahlung, with leptonic Z decays, and ZZ fusion production modes
- Main difference between electron and muon Z decay channels comes from Bhabha events, negligible in Z to two muons channel and main source of background in the electron decay one
- Sensitivity at the same level for Z to two muons and Z to two electrons search channels

- Searches with Z decaying hadronically @250 GeV (not full simulation background @ 550 GeV) ongoing

Future Higgs factories are able to exclude couplings down to a few percent of the SM-Higgs equivalent