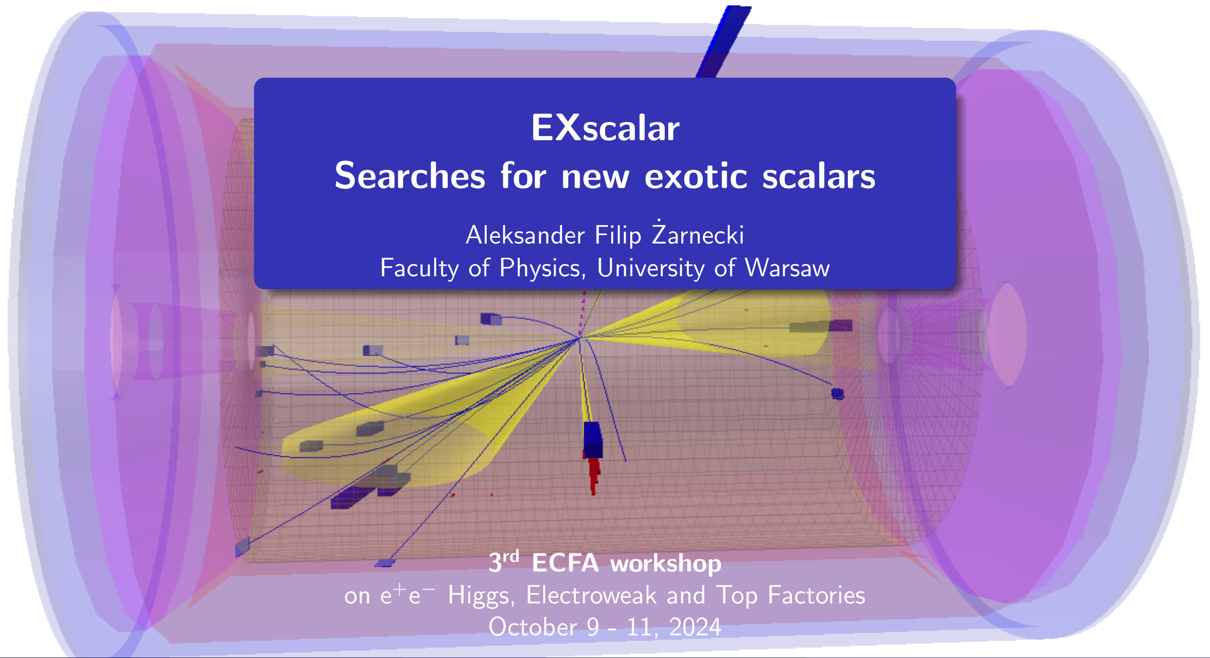


EXscalar
Searches for new exotic scalars

Aleksander Filip Żarnecki
Faculty of Physics, University of Warsaw

3rd ECFA workshop
on e^+e^- Higgs, Electroweak and Top Factories
October 9 - 11, 2024

Outline:

Mostly based on results presented at this workshop.

Many thanks to all who contributed to the presented results!

Apologies for all omissions and mistakes...

EXscalar - Searches for new exotic scalars

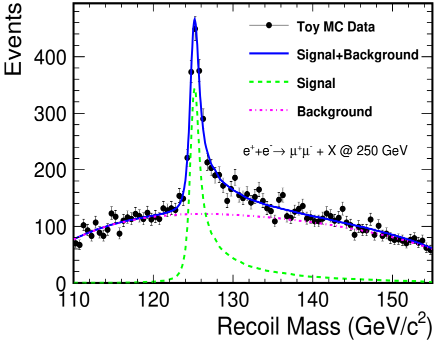
1. Introduction

2. Results from Focus Topic studies
   - Motivation
   - New scalar production in scalar-strahlung
   - New scalar production in decays
   - Other searches

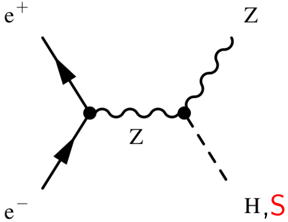
3. Conclusions

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

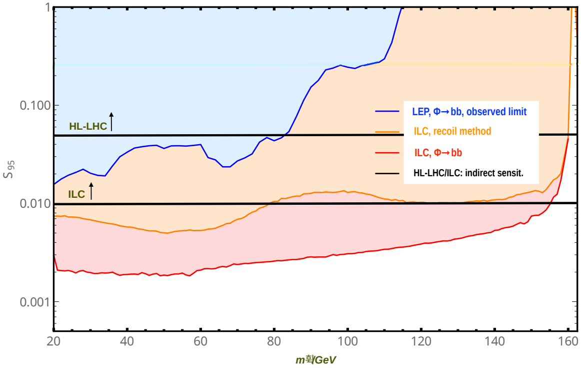


But production of additional, light exotic scalar states is still not excluded by the existing data!

Generator level estimates

arXiv:1801.09662

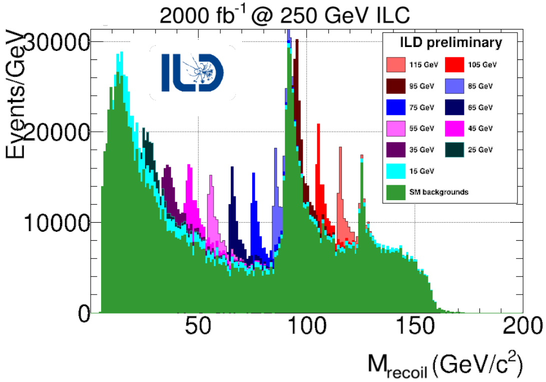
Projection of LEP results: dedicated search should result in stronger constrains than resulting from precision measurements of Higgs couplings.

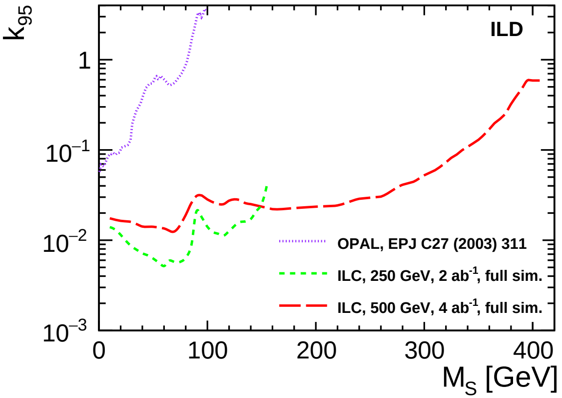


Expected 95% C.L. limits on the scalar production cross section σ/σ_{SM} assuming standard BRs

Previous studies

Decay independent search   Full simulation   arXiv:1902.06118   arXiv:2005.06265





Based on recoil mass

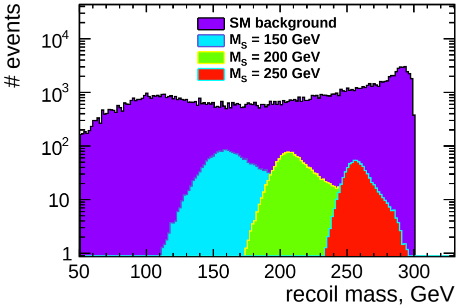
$$e^+e^- \rightarrow Z\ S \rightarrow \mu^+\mu^- + X$$

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

Previous studies

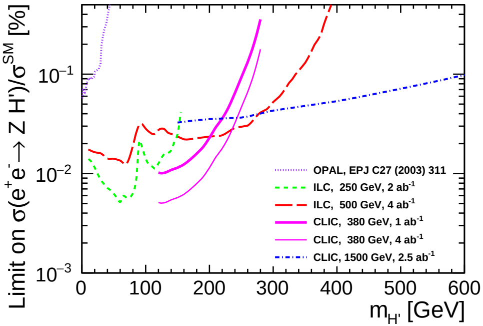
Invisible decays previously studied only for CLIC @ 380 GeV arXiv:2002.06034 arXiv:2107.13903

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

Focus topic

Theoretical and phenomenological targets (1)

Higgs factories are best suited to search for light exotic scalars in the process:

$$e^+e^- \to Z\ \phi$$

Production of new scalars can be tagged, independent of their decay, based on the recoil mass.

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

For maximum sensitivity, feasibility of including hadronic Z decays should be explored.

Focus topic

Theoretical and phenomenological targets (2)

As as second benchmark scenario for the EXscalar focus topic,
light scalar pair-production in 125 GeV Higgs boson decays is proposed:

$$e^+e^- \to Z\ H \to Z\ \phi\ \phi$$

Here again, different decay channels should be considered, both SM-like and exotic.

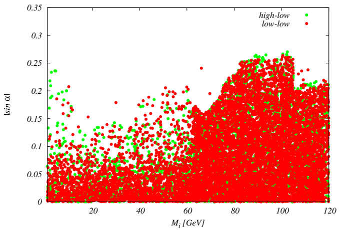
While new scalar states could in general be long-lived, only scenarios with prompt decays are included in this focus topic (while a dedicated topic focuses on LLPs, see next presentation).

EXscalar - Searches for new exotic scalars

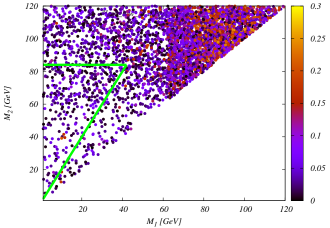
EXscalar - Searches for new exotic scalars

Singlet extensions [TR, arXiv:2203.08210 and Universe 8 (2022) 286]

TRSM: 2 real singlets [TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J.C 80 (2020) 2, 151]



mass and mixing angle

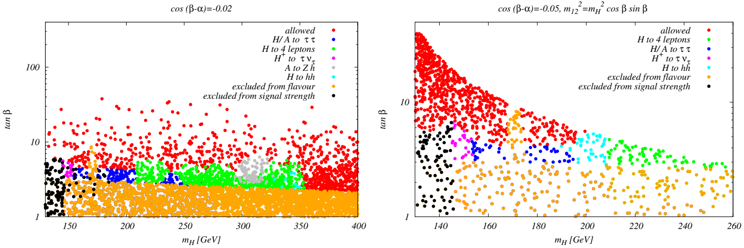


case with two light scalars;
color coding: h_1 rescaling

- **low-low:** both additional scalars below 125 GeV; **high-low:** one new scalar above 125 GeV

2HDM parameter space for fixed $\cos(\beta - \alpha)$, Type I

TR, ArXiv:2409.19657



$$m_H = m_A = m_{H^\pm}$$

[using thdmTools, Biekoetter ea, JHEP 01 (2024) 107]

Typical processes at Higgs factories

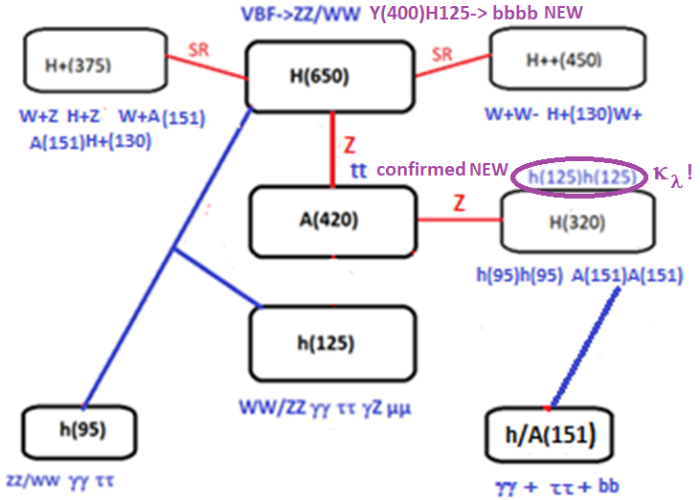
various production modes possible

1) **easiest example:** $e^+ e^- \rightarrow Z\, h_1$, onshell production interesting up to $m_1 \sim 160\,\mathrm{GeV}$
2) in **models with various scalars:** e.g. also $e^+ e^- \rightarrow h_1\, h_2$ (e.g. from 2HDMs); example processes and bounds from LEP in Eur.Phys.J.C 47 (2006) 547-587

   again: for onshell production, $\sum_i m_i \leq 250\,\mathrm{GeV}$
3) another (final) option: **look at** $e^+ e^- \rightarrow h_i\, Z,\; h_i \rightarrow h_j\, h_k$

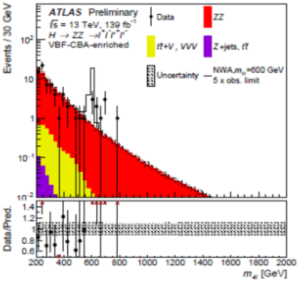
already quite a few studies for 1), 3) available

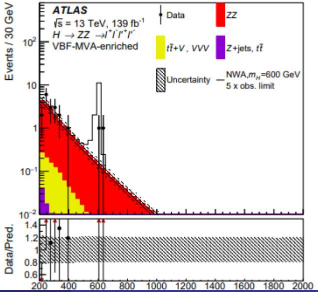
SUMMARY OF BSM SCALAR CANDIDATES



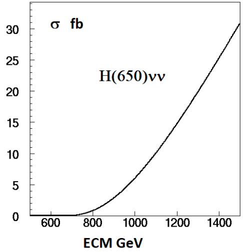
VBF->ZZ

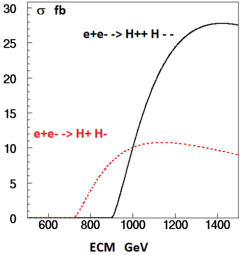
- The ATLAS **cut based analysis** again shows indications around 650 GeV
- The ATLAS MVA analysis *2103.01918* tuned for a scalar reduces this indication while one predicts almost no reduction for a scalar
- This behaviour is simply interpreted assuming that X(650) is a tensor
- If, for instance, one selects against DY |cosθ |<0.8, one keeps 80 % for a scalar, but only 40 % for a tensor





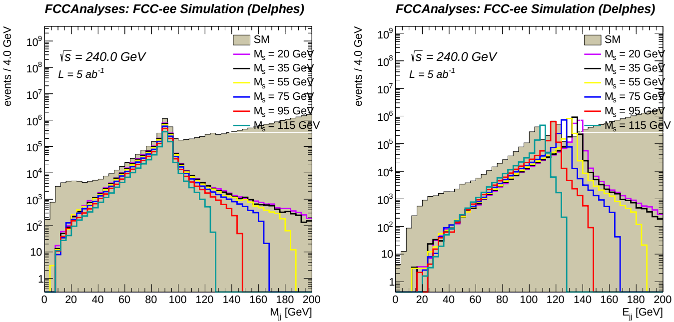
e+e- collider reach





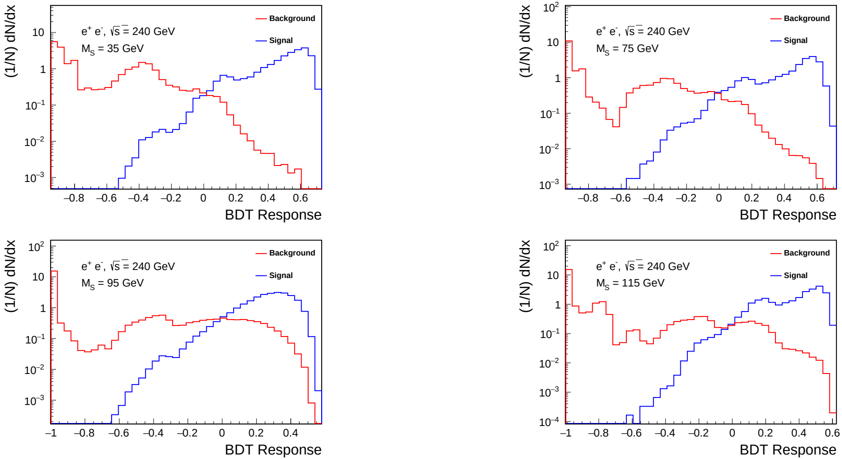
- **ILC** should provide **8000 fb-1 at 1 TeV** needed to reach H++, H(650) and H(320)
- **H(650)** is expected through VBF (beam polarisation allows a factor ~2 gain, not included in above cross sections)
- It can benefit from an increased energy provided by **CLIC**
- Using an **e-e- collider** one could also produce H^{--} through VBF with polarized beams, giving ~100 fb at 1 TeV

Reconstruction of Z boson: Invariant Jet Mass



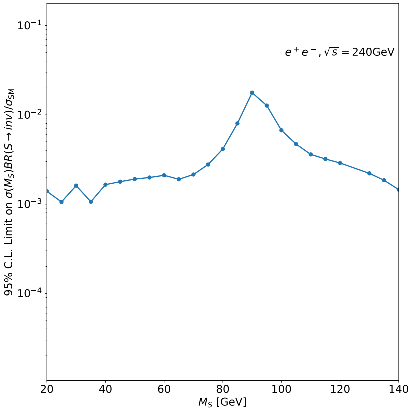
- This variable is built by combining four-vector of two jets and finding the pair with its invariant mass closest to that of the mass of Z boson (91 GeV).
- The cut on Z mass helps eliminating events not consistent with the Signal process (i.e., absence of Z boson).

Machine Learning Results: BDT Response



- The above plots show the BDT response for four signal hypothesis, namely, $M_S = 35,\ 75,\ 95,\ 115$.

Limit on Production Cross-section x Branching Ratio



- This limit is obtained by taking a product of $\alpha_{95\%C.L.} \times \sigma(e^+e^- \to q\bar{q}S) \times Br(S \to inv.)/\sigma(e^+e^- \to q\bar{q}H)$ assuming $Br(S \to inv.) \simeq 10\%$

Motivation and conditions current studies

Reimplementation of previous analysis with current experimental conditions and full simulation software

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

Different Z decays modes want to be covered

Samples:

- Background using new SM 250 GeV samples generated with Whizard v.2.8.5, the SetA beam-spectrum, simulation and reconstruction with the ILD_l5_o2_v02 model, and ILCSoft v02-02-01
- Signal generated with Whizard v.2.8.5, the SetA beam-spectrum, detector simulation done by sgv.

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

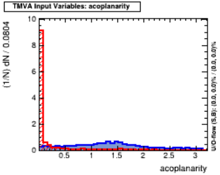
DESY.

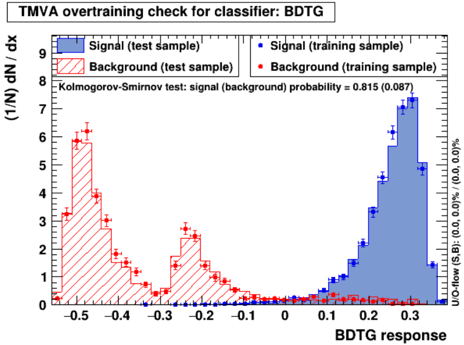
4

Teresa Núñez: Decay-mode independent search

Training against 2f background (2f-mtva)

Exotic Scalar mass 80 GeV





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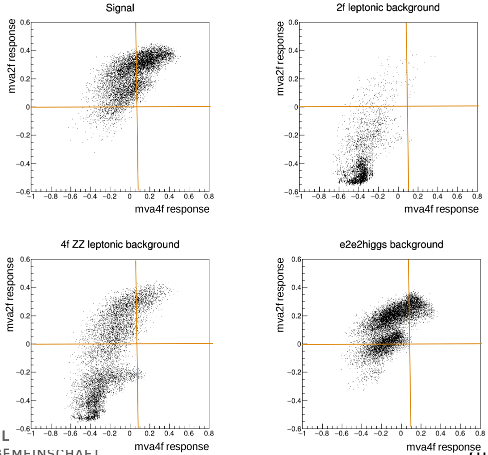
9

Illustration cuts on variable distributions



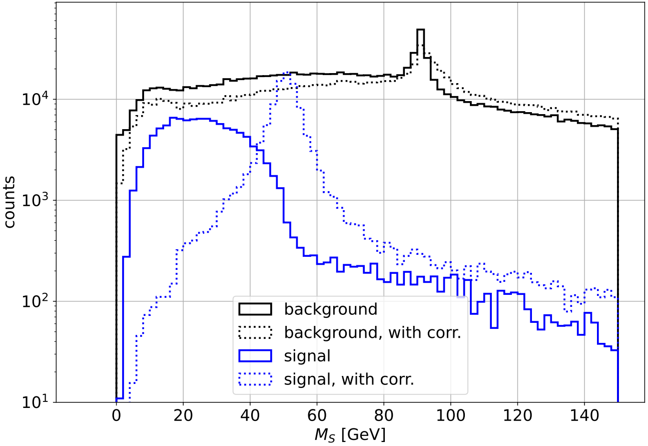
Cuts:
mva2f response > 0
mva4f response > 0.1

Scalar mass 90 GeV

Event reconstruction

Kamil Zembaczyński (University of Warsaw)

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



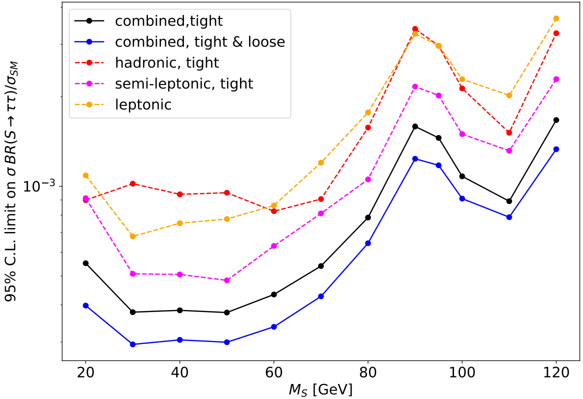
Signal for scalar mass of **50 GeV**. Normalized to 1% of the SM production cross section for the considered scalar mass.

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

Results

Kamil Zembaczyński (University of Warsaw)

Cross section limits for $\sigma(e^+e^- \rightarrow Z\,S) \cdot BR(S \rightarrow \tau\tau)$
for different event categories and combined analysis



Semi-leptonic sample most sensitive to new scalar production

Significant improvement when including loose-selection categories

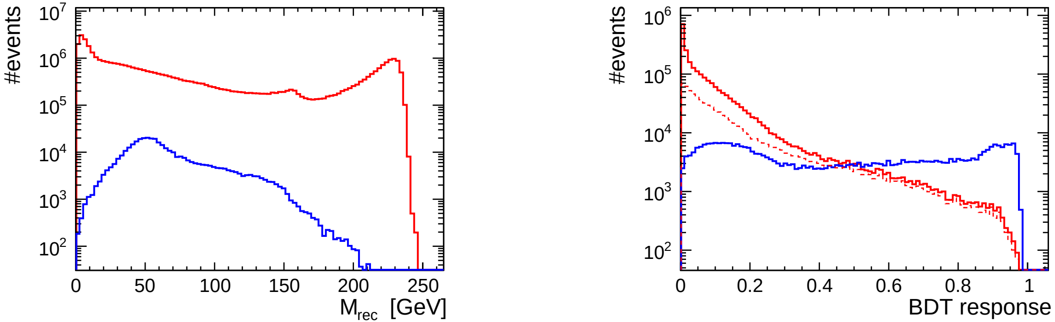
Marginal impact of normalization uncertainties (theory + lumi).

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.



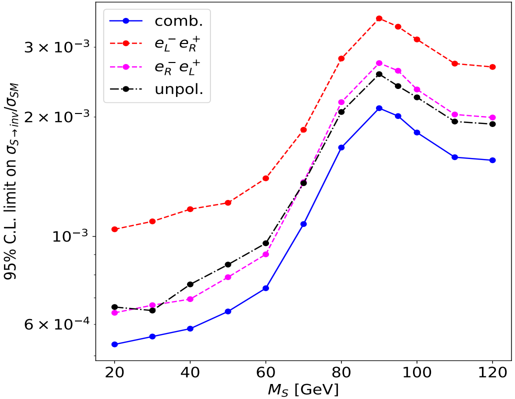
Signal normalized to 1% of SM cross section.

Dashed: $qq\ell\nu$ background.

Results

Kamil Zembaczyński (University of Warsaw)

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

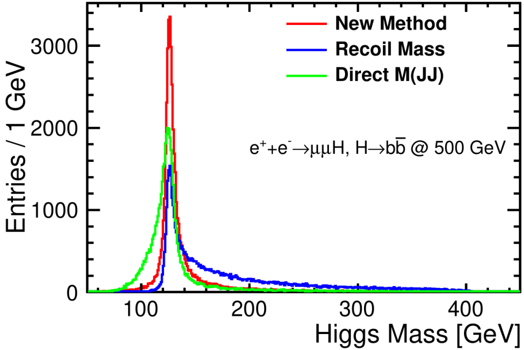
Polarisation results in about 20% improvement in the sensitivity.

Event reconstruction

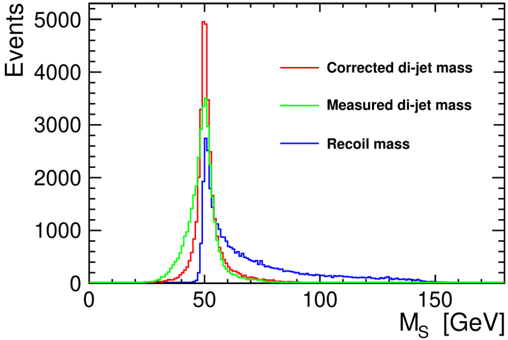
Bartłomiej Brudnowski (University of Warsaw)

Focusing on leptonic decays, $Z \to e^+e^-/\mu^+\mu^-$; huge W^+W^- background for hadronic decays

Full simulation for H_{125} at 500 GeV



Fast simulation for 50 GeV scalar at 250 GeV

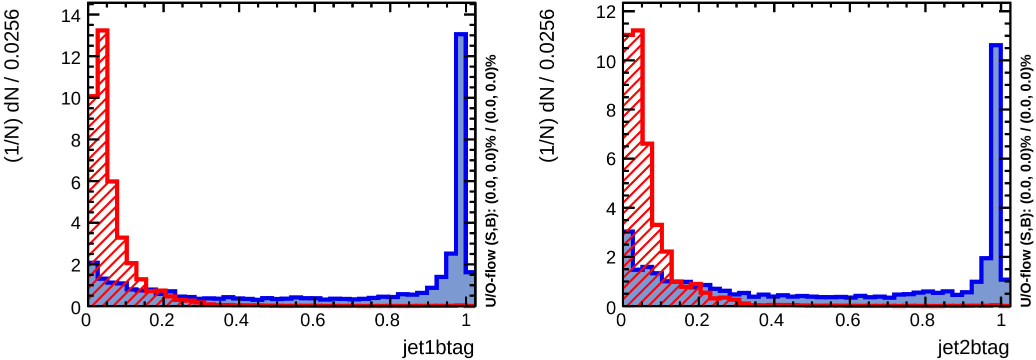


ILD-PHYS-PUB-2019-001

Flavour tagging

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

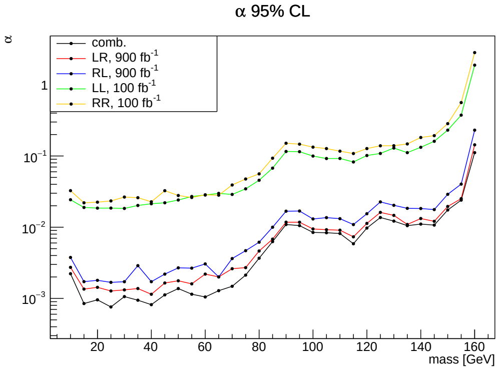
Tagging of b jets crucial for background suppression.
Use SM background full simulation samples for more reliable estimate of selection efficiency.
Clear separation of signal events from (mostly light flavour) SM backgrounds



Results

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

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



Little impact of the beam polarisation
Background dominated by ZZ production

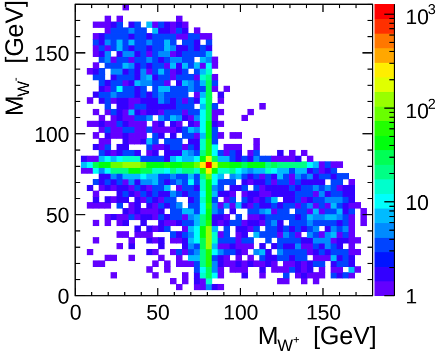
Simulation study

with Tania Robens, Yang Ma, Mohamed Ouchemhou

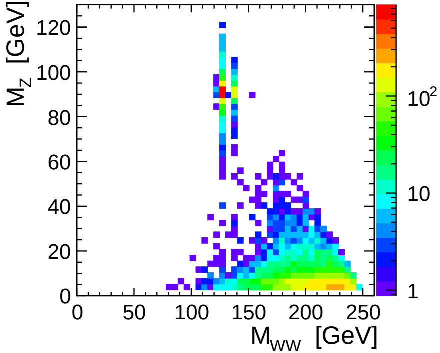
Correlation of reconstructed boson masses on generator level

TRSM model with additional 140 GeV scalar at $\sqrt{s}$ =250 GeV

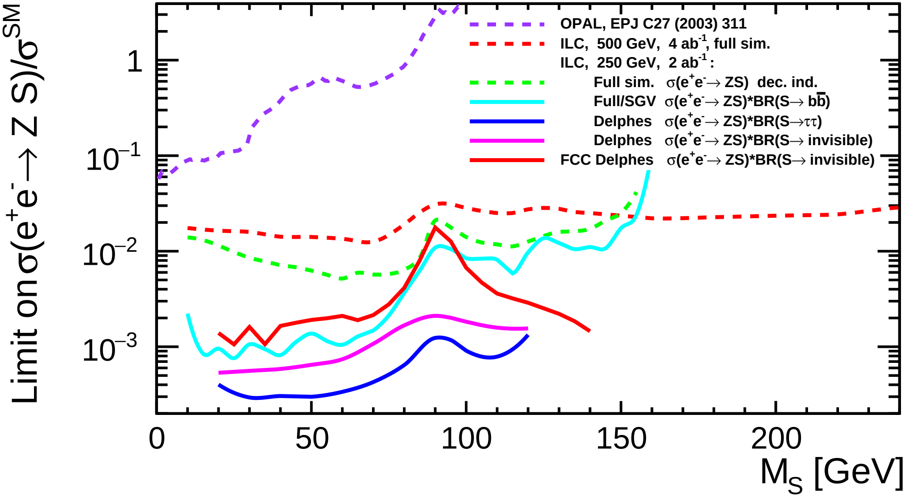
All events



Clear separation of scalar production



Summary of results



Exotic decay of the Higgs boson into two light pseudoscalars

- Current analysis is a search for a pair of light (20-60 GeV) Higgs bosons from SM Higgs decay produced in association with a Z boson in 250 GeV e^+e^- collider.

$$e^+e^- \to Z\,(\to \boldsymbol{\mu}^+\boldsymbol{\mu}^-)\,H \to a\left(\to \boldsymbol{b\bar{b}}\right)a(\to \boldsymbol{\tau}^+\boldsymbol{\tau}^-)$$

$$e^+e^- \to Z\,(\to \boldsymbol{e}^+\boldsymbol{e}^-)\,H \to a\left(\to \boldsymbol{b\bar{b}}\right)a(\to \boldsymbol{\tau}^+\boldsymbol{\tau}^-)$$

- The two considered backgrounds are ZZ and ZH

- Samples have been generated using Madgraph5, hadronized with Pythia8, simulated for detector responses with Delphes

Channels	XS (b)	# of Events Generated
$e^+e^- \to Z(\to ll)\,H \to a(\to b\bar{b})\,a(\to \tau^+\tau^-)$	6.60×10^{-15}	10000
$e^+e^- \to Z(\to ll)\,H$	6.60×10^{-15}	1000000
$e^+e^- \to Z(\to ll)\,Z(\to f\bar{f})$	3.52×10^{-14}	1000000

Event Selection

Z→ll selection:

- ❑ Pair of opposite sign leptons consistent with Z boson

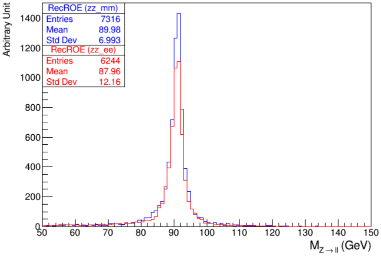
a→ττ selection:

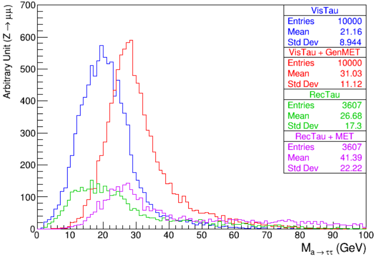
- ❑ Pair of opposite sign τ, adding MET (in lie of neutrinos) to mass
- ❑ A dedicated tau Reco algorithm developed

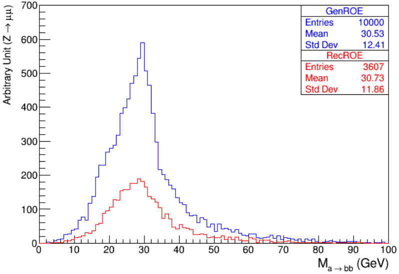
a→bb selection (ROE):

- ❑ b-Jet reco efficiency is low, thus ROE is defined

$$\text{RecROE} = \sum_{i}^{\text{excl } l \,\&\, \tau} \text{tracks}_i + \sum_{i}^{\text{excl } l \,\&\, \tau} \text{Photons}_i + \sum_{i}^{\text{excl } l \,\&\, \tau} \text{NHadrons}_i$$

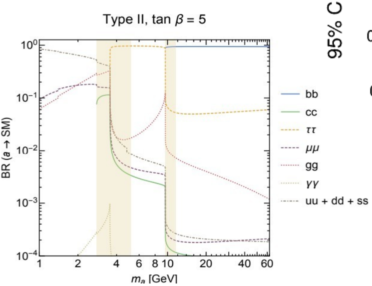


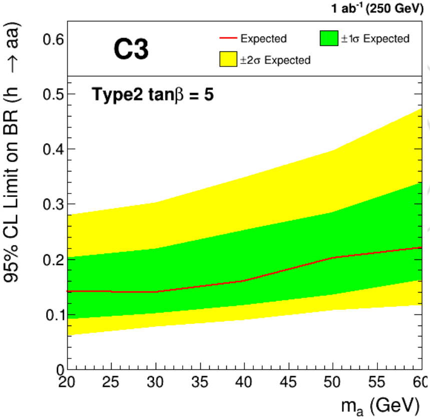


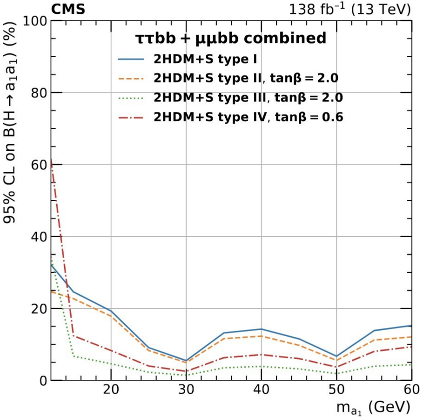


Model-Dependent limit (Type II 2HDM)

a Boson Mass (GeV)	BR	BR
20	0.93	0.0485
30	0.93	0.0488
40	0.93	0.049
50	0.93	0.0495
60	0.93	0.05



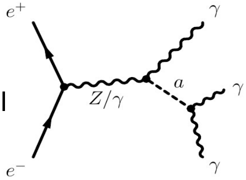


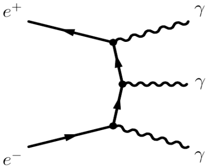


- ❑ Not an apple to apple comparison (different model parameters)
- ❑ Limit is comparable with combination of CMS 2b2mu and 2b2tau results

3γ ALP signal and backgrounds

Signal





Dominant background for 3γ analysis

Generation chain:

- LHE files produced with MG5MC@NLO
- Shower with PYTHIA8, detector simulation with DELPHES, inside FCC software
- PYTHIA and IDEA DELPHES card as for Winter23 production, output as EDM4HEP files
- Write out flat ntuple from EDM4HEP with FCC software and run analysis

Signal samples for M_a between 0.1 and 85 GeV and for the Z-pole FCC-ee run, normalise to 205 ab^{-1} as per midterm report

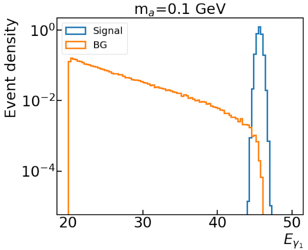
γ+MET analysis

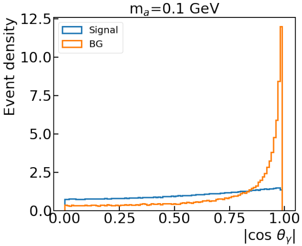
Relevant mass range below ~2~GeV → signature is a monochromatic photon of energy ~45.5 GeV and nothing else in the detector

Consider two backgrounds: irreducible: $e^+e^- \to \gamma\nu\nu$

reducible: e+e-→γe+e- where the electron and positron are outside detector acceptance (|η|<3). By requiring the photon to be within |η|<2.6 and with energy at the kinematic limit this background is reduced to very small

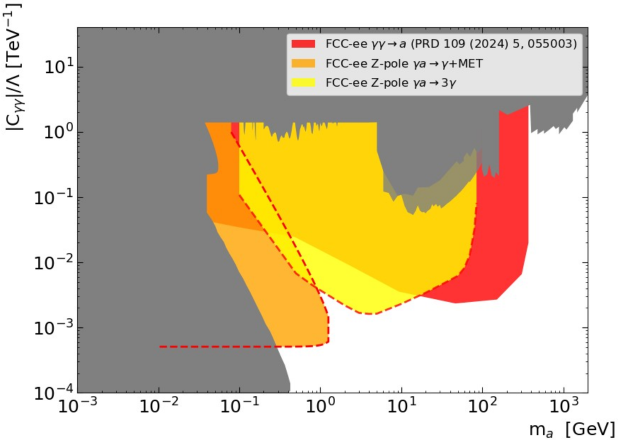
Backgrounds produced with MG5MC@NLO and passed through the usual PYTHIA-DELPHES chain





Two variables characterise the event, energy and polar angle of photon.
Combine them through XGB as for prompt analysis

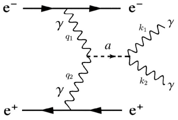
Combined plot FCC-ee



Grey areas :existing exclusions taken from ATLAS plot, to be updated with newest results

Yellow and orange areas are the two analyses of this talk

Red area is analysis of Rebello Teles et al. addressing ALP production in photon-photon fusion



The Inert Two-Higgs-Doublet model (IDM)

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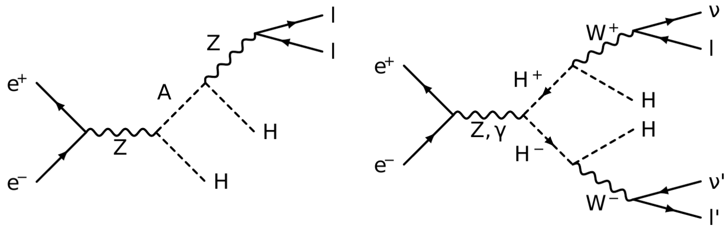
- Two Higgs-Doublet model: 5 scalars, h, H, A, H+, H-.
- h is the SM Higgs with constraints from SM measurements.
- Add Z2 symmetry:$\phi_D \to -\phi_D$,$\phi_S \to \phi_S$, SM $\to$ SM.
- New scalars do not couple to fermions and are pair-produced.
- Dark Matter candidate(s): choose H.
- Five free parameters: m$_H$, m$_A$, m$_{H^\pm}$, λ_{345}, λ_2.

Final state considered: 2ℓ(=e or μ) + HH, mainly produced through AH and H$^+$H$^-$



Main variables for background rejection

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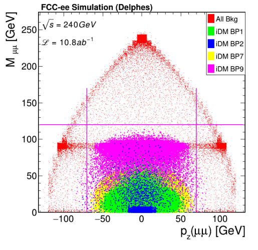
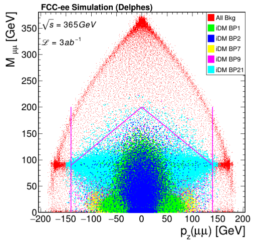
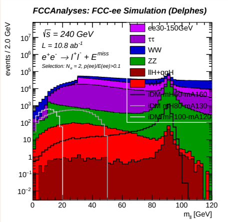
Powerful 1st level rejection using 2-D cut



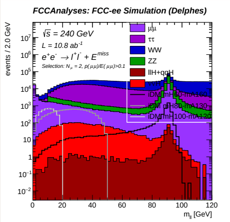


- Reproducing previous results from [arXiv:2002.11716].
- Next step: enhance signal with machine learning.

M_{ee} after ee selection



$M_{\mu\mu}$ after $\mu\mu$ selection



Conclusion

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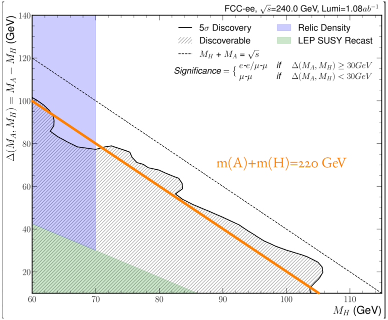
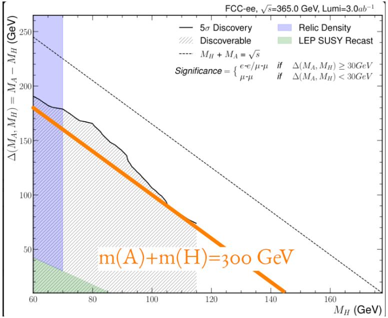
- Explored the IDM model with FCC-ee at $\sqrt{s}$ =240 (365) GeV.
- Reproduced CLIC/ILC setup results, extending a little the reach with parametric Neural Network approach with smooth limit/significance extraction.
- Will fix the model parameters to "allowed" choices but not expecting large impact on the sensitivity.
- Next: ready to incorporate realistic systematic uncertainty scenarios !





Conclusions

Many activities, interesting results already available, more results still coming!

Assumed scope of the EXscalar section of the report

- Motivation, models and constraints
- Scalar search in $e^+e^- \to S\ Z$:
  - decay independent (based on recoil mass): full sim. results coming
  - $S \to b\bar{b}$: new full sim. study
  - $S \to \tau\tau$: new fast simulation study
  - $S \to inv$: new fast simulation results (both from ILC and FCCee)
  - $S \to W^+W^-$: much more work needed (!)
- Scalar production in (exotic) Higgs decays: $H \to aa$
- Scalar production in (exotic) Z decays: $Z \to S\gamma$