Search for invisible decays of light scalars at Future Lepton Collider

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October 9, 2024

3rd ECFA workshop on e+e- Higgs/EW/Top Factories, Paris, 9-11 October 2024

Overview

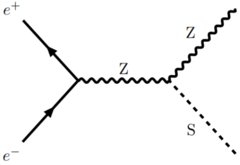
All results in this presentation are preliminary.

All errors that remain are mine.

Motivation

Motivation

- $e^+e^- \to Z\ S$ (scalar-strahlung) process could be used to probe new low mass scalar using Recoil Mass analysis technique.



- One can use the decay products of Z boson to probe this process.
- Light exotic scalar states at low masses are not excluded by existing data.
- We have considered hadronic decay of the Z boson which has a $Br(Z \to q\bar{q}) \simeq 70\%$ and invisible decay of new scalar - $S \to inv$ (which may include Dark Matter).
- This study considers the center of mass energy as 240 GeV.
- Previously, this was studied for CLIC at 380 GeV. Eur. Phys. J. Plus 136, 160 (2021)

Event Samples

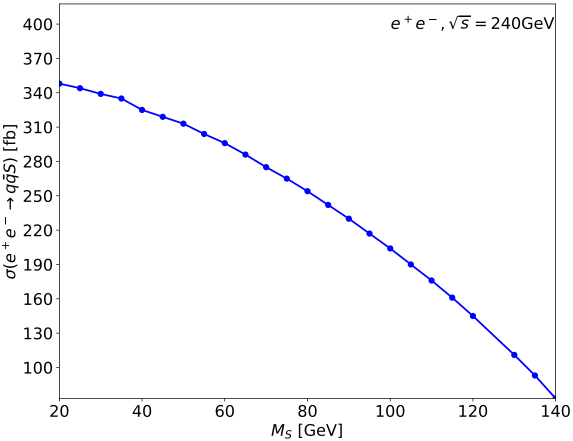
Simulation Toolbox

- We have used MadGraph5_aMC@NLO to simulate all the signal and background hard processes.
- Pythia8 is used for parton shower.
- FastJet is used for jet clustering. In particular, we have used the Durham k_T-algorithm in the njet=2 mode.
- Delphes is used for the fast detector simulation of IDEA detector (FCC).
- The above chain of softwares is handled using the Key4HEP framework and FCCAnalyses software.

Signal Event Samples

- Signal: $e^+e^- \to Z\ S$, where S is a new scalar at center of mass energy set to 240 GeV.
- Here we have considered the hadronic decay of the Z boson into two jets.
- Generation of this sample is done using the SM model implemented in `MadGraph5_aMC@NLO`.
- Currently, we produce the BSM samples by considering the decay of SM Higgs, as implemented in the SM model in MG5, to four neutrinos via ($H \to ZZ \to v\bar{v}v\bar{v}$) and we vary the SM Higgs mass.
- A set of signal samples are considered with $M_S \in [20, 140]$.

Signal Cross Section



Cross Section for $e^+e^- \to Z\ S$ as a function of scalar mass, for an SM-like scalar.
The cross-section reduces with increase in Scalar Mass.

Background Event Samples

- All background samples have been generated using the same chain of tools as for signal.
- Background consists of a combination of jets, leptons, and neutrinos.
- We have considered the final states consisting of two jets, four jets, two jets + two leptons, two jets + neutrinos, two jets + lepton + neutrino.

Cross Section of Background Processes

Background Process	Cross Section (pb)
Without SM Higgs boson	
qq	12.21
qqqq	0.616
qqll	0.166
qqvv	0.359
qqlv	3.53
qqlvvv	0.000621
SM Higgs Boson	
qqh	0.129
llh	0.0152
vvh	0.0540

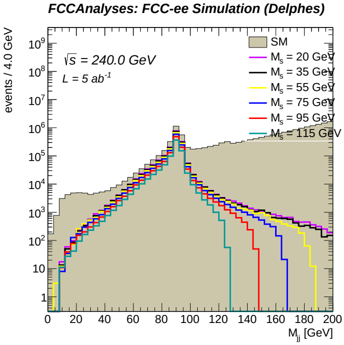
Table: Cross sections for various background processes.

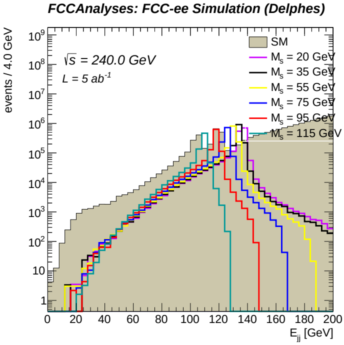
Cut-based Analysis

Cut-based Analysis

- The Signal considered in this study consists of two jets and missing momentum, where the jets are coming from the Z boson and missing momentum contribution comes through the decay of New Scalar.
- The analysis considers an integrated luminosity $\mathcal{L} = 5\ \text{ab}^{-1}$ Eur. Phys. J. C 79, 474 (2019).

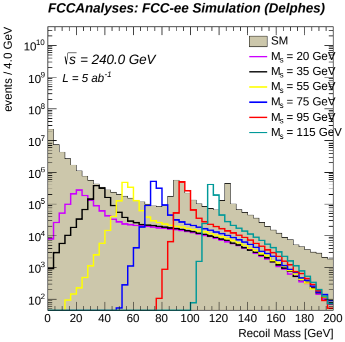
Reconstruction of Z boson: Invariant Jet Mass





- 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).

Recoil Mass Reconstruction



- Recoil mass is given by: $M_{\mathrm{Recoil}} = s + m_Z^2 - 2E_z\sqrt{s}$
- A variable cut on M_{Recoil} is applied in a window of a given $M_S \pm 20$ GeV.
- Peaks seen in SM distribution are from ZZ (at 90 GeV) and ZH events (at 125 GeV).

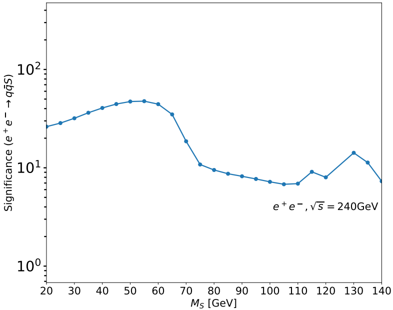
Results: Cutflow

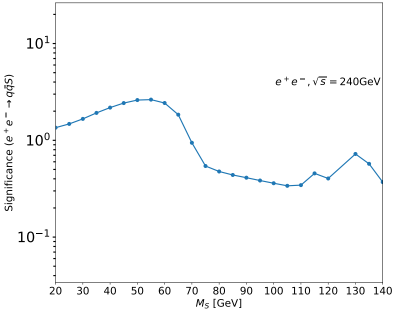
- The significance is evaluated after applying all the aforementioned cuts.
- $\sigma = S/\sqrt{S+B}$ is used; where S is the Signal yield and B is the Background yield.

Cut	**Range/Cut value**
M_Z	[80, 100] GeV
Jet's $\sqrt{d_{23}}$	$<$ 60 GeV
Jet's $\sqrt{d_{34}}$	$<$ 40 GeV
M_{Recoil}	$M_{\mathrm{Recoil}} \pm 20$ GeV
Missing Momentum	Varying cut

d_{23} is the squared transverse momentum of the less energetic particle relative to the more energetic one in a clustering from 3 to 2 jets. Gavin Salam's Talk

Results: Significance versus Scalar Mass





- Significance is high for lower Scalar mass ranges. However, we see a drop in significance near Z mass as well as near Higgs mass as these regions have significant contributions from SM (from ZZ and ZH processes).
- Plot on right assumes "typical" suppression with $\sin\theta \sim 0.24$ for signal

Machine Learning

Machine Learning

- We have used the TMVA framework within CERN ROOT for Machine Learning.
- For training, all background samples were grouped together as SM background.
- Each signal sample (based on scalar mass) is then trained separately against the combined SM background.
- We have considered Boosted Decision Trees with the following parameters:
  - Number of Trees: 100
  - Minimum node size: 3%
  - Maximum Depth: 3
  - Boost: AdaBoost (Adaptive Boosting)
  - Separation Type: GiniIndex
  - nCuts: 20
- Any other parameter not specified above is then used with its default value set by TMVA.

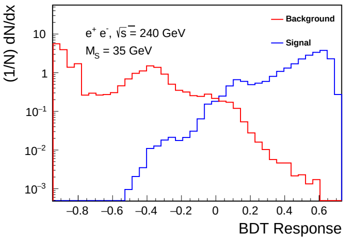
Machine Learning: Training Variables

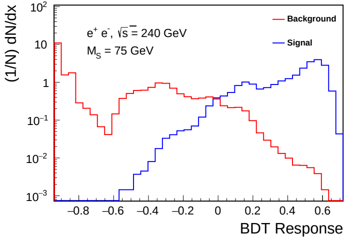
We have used the following 14 variables for machine learning training:

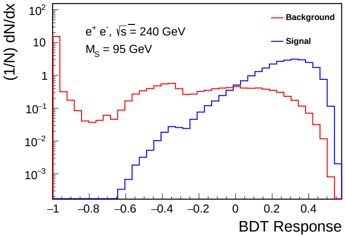
- Four-momentum variables for both jets (8 variables)
- Z candidate invariant mass (1 variable)
- Z candidate energy (1 variable)
- Missing Momentum (1 variable)
- $\sqrt{d_{23}}$ and $\sqrt{d_{34}}$ variable from jet clustering algorithm (2 variables)
- Recoil Mass (1 variable)

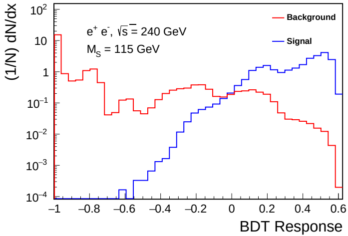
No cuts are applied on data used for Machine Learning algorithm.

Machine Learning Results: BDT Response



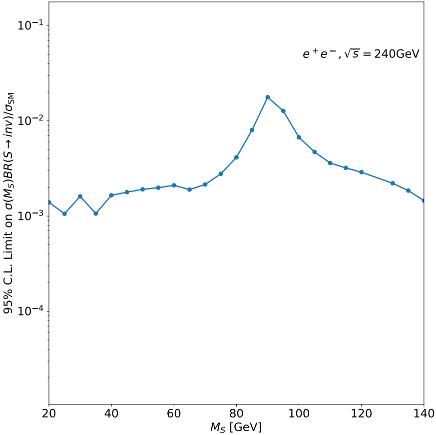






- The above plots show the BDT response for four signal hypothesis, namely, $M_S = 35,\ 75,\ 95,\ 115.$

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 $Br(S \to inv.) \simeq 10\%$

Summary and Outlook

Summary and Outlook

- We have studied the invisible decays of a new scalar particle in $e^+e^- \to Z\ S$ process.
- We used both a cut-based and Boosted Decision Tree based approach to discriminate events.
- For the cut-based approach we evaluated the Significance for each mass point.
- For the BDT based approach we evaluated limits on $\sigma(e^+e^- \to q\bar{q}S) \times Br(S \to inv)$.
- Future work will address the inclusion of 125 GeV - for a more realistic scenario.
- Comparison with Whizard generated samples [if needed]

Acknowledgements

Acknowledgements

We would like to thank Prof. Aleksander Filip Zarnecki for discussions.

Backup

New Scalar Cross-Section

M_S **[GeV]**	$\sigma(e^+e^- \to ZS)$ **[fb]**	M_S **[GeV]**	$\sigma(e^+e^- \to ZS)$ **[fb]**
15	351	80	254
20	348	85	242
25	344	90	230
30	339	95	217
35	335	100	204
40	325	105	190
45	319	110	176
50	313	115	161
55	304	120	145
60	296	125 (SM)	129
65	286	130	111
70	275	135	93
75	265	140	72

Fixed Cuts and Variable Cuts

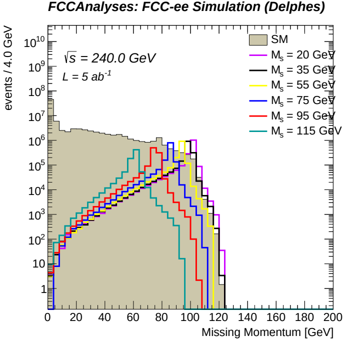
Fixed Cuts:

- Invariant mass of two jets is required to be consistent with the Z boson: $M_{jj} \in [80, 100]$ GeV.
- Jet's $\sqrt{d_{23}} < 60$ GeV.
- Jet's $\sqrt{d_{34}} < 40$ GeV.

Variable Cuts:

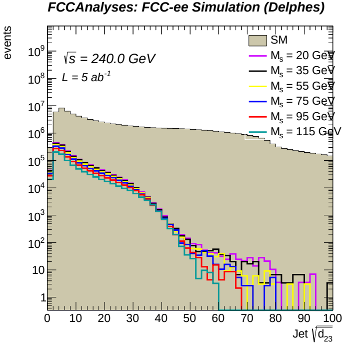
- Missing Momentum: Missing momentum varies as the scalar mass changes. Therefore a varying cut is used for all Signal samples (cut varies by 2 GeV).
- Recoil Mass: A variable cut is applied on recoil mass. For all the Signal sample this cut is applied such that events in the range $M_{\mathrm{recoil}} \pm 20$ GeV are selected.

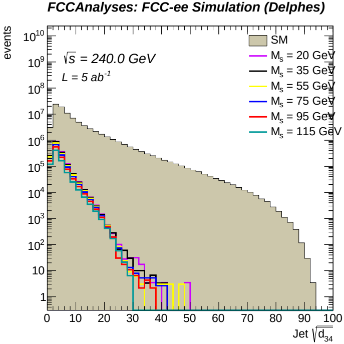
Missing Momentum



- Signal consists of Missing momentum arising from the simulation of neutrinos escaping the detectors.
- As we see, most signal is concentrated in the region with $P^{miss} > 10$ GeV. However, a variable cut on Missing momentum helps as Missing Momentum distribution changes with Scalar mass.

$\sqrt{d_{23}}$ and $\sqrt{d_{34}}$ variable from jet clustering algorithm





- These variables allow us to distinguish two jet event from three jet event (d_{23}) and three jet event from four jet event (d_{34}).
- We have applied the following cut on the variables:
  - Jet's $\sqrt{d_{23}} < 60$ GeV.
  - Jet's $\sqrt{d_{34}} < 40$ GeV.

Limit on Production Cross-section

- We obtain the limit on $\sigma(e^+e^- \to q\bar{q}S) \times Br(S \to inv)$ using the BDT response.
- This is obtained by using the following equation:

$$\alpha_{95\%C.L.} = 1.64 \times \delta_\alpha = 1.64 \times \sqrt{\frac{1}{\sum_{i=1}^{N_{\rm bin}} \frac{S_i^2}{B_i}}} \quad (1)$$

- Here S_i correspond to the number of Signal events in bin i in the BDT response and B_i correspond to number of Background events in that bin.