Searches for new exotic scalars at the ILC

Analysis of the scalar particle S decay channel into two τ leptons

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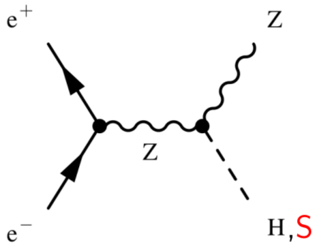
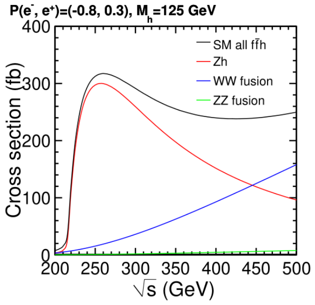
Outline

Introduction

Exotic scalar production in scalar-strahlung process is considered.





arXiv:1306.6352

$Z \to q\bar{q}$ and $S \to \tau^+\tau^-$ is assumed.

τ can decay into μ or e $\implies$ look for hadronic (4 jets), semi-leptonic (3 jets and lepton) and leptonic (2 jets and 2 leptons) final states.

ILC H-20 running scenario at 250 GeV.

Event and detector simulation

Signal and background samples generated with WHIZARD 3.1.2 using built-in SM_CKM model.

Signal samples generated by varying H mass in the model and forcing its decay to $b\bar{b}$ or $\tau^+\tau^-$.

All relevant four-fermion final states considered as background.
SM-like Higgs boson contribution included in the background simulation.

ISR and luminosity spectra for ILC running at 250 GeV taken into account

H-20 running scenario for ILC assumed with $\pm 80\% / \pm 30\%$ polarisation for e^-/e^+ beams.

"pure" initial states ($\pm 100\%$ polarisation) generated and mixed
$\Rightarrow$ only two combinations (LR and RL) relevant for most processes

Fast detector simulation with Delphes ILCgen model.

Sample mixing and expected luminosities

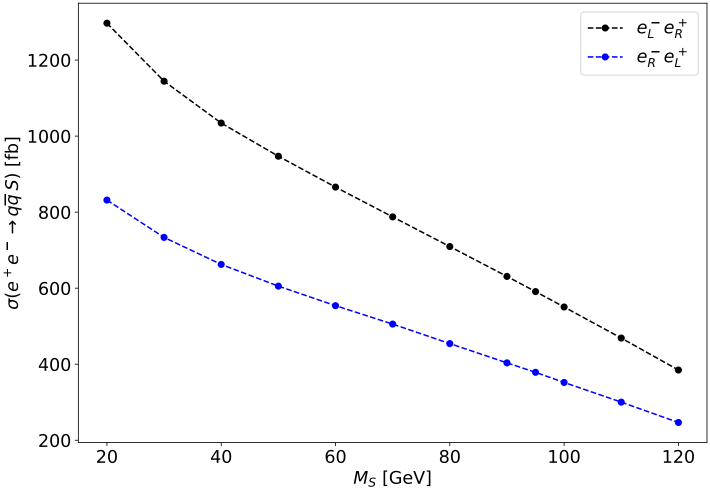
	Generated sample			
	eLpR ($e^-_L e^+_R$)	eRpL ($e^-_R e^+_L$)	eLpL ($e^-_L e^+_L$)	eRpR ($e^-_R e^+_R$)
Beam polarisation setting	Weight factor			
	$\frac{(1-P_{e^-})(1+P_{e^+})}{4}$	$\frac{(1+P_{e^-})(1-P_{e^+})}{4}$	$\frac{(1-P_{e^-})(1-P_{e^+})}{4}$	$\frac{(1+P_{e^-})(1+P_{e^+})}{4}$
$(-,+)$	0.585	0.035	0.315	0.065
$(+,-)$	0.035	0.585	0.065	0.315
$(-,-)$	0.315	0.065	0.585	0.035
$(+,+)$	0.065	0.315	0.035	0.585
unpol.	0.25	0.25	0.25	0.25
	Expected H-20 sample luminosities [fb^{-1}]			
$(-,+)$	526.5	31.5	283.5	58.5
$(+,-)$	31.5	526.5	58.5	283.5
$(-,-)$	31.5	6.5	58.5	3.5
$(+,+)$	6.5	31.5	3.5	58.5
unpol.	500	500	500	500

Generated luminosities and event weights

	L_{gen} for generator polarisation [fb^{-1}]			
background process	LR	RL	LL	RR
$qqqq$	69.9	103	-	-
$qq\tau\tau$	338	633	-	-
$qqll$	97.3	156	384	384
$qq\nu\nu$	93.9	254	-	-
$qql\nu$	103	576	850	849
$qq\tau$v	107	1150	-	-
$\tau\tau$ll	487	556	689	688
$\tau\tau\tau\tau$	836	13500	-	-
qq	15.7	14.4	-	-
$qqll\nu\nu$	1110	1880	-	-

$$w = \frac{N_{exp}}{N_{gen}} = \frac{\sigma_{exp} N_{exp}}{L_{gen}} = \frac{L_{exp}}{L_{gen}}$$

Signal cross section



Cross section for $e^+e^- \to q\bar{q}\,S$ ($q\bar{q} \sim Z$) process at Whizard level as a function of scalar mass

Events pre-selection

Only events without isolated photons and with appropriate number of jets were accepted.
Events divided into 5 categories.

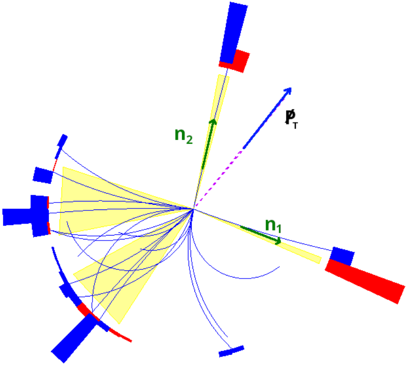
category	isolated leptons	tight	loose
hadronic	zero	4 jets including 2 with τ-tag	4 jets, 1 with τ-tag and other lightest jet as second τ- tag jet
semi-leptonic	one	3 jets including 1 with τ-tag	3 jets with no τ-tag, lightest jet as τ- tag jet
leptonic	two	two jets without τ-tag	

S mass reconstruction

High τ boost and ν emitted in τ jet direction $\implies$ ν and τ jet collinearity

From transverse momentum balance:

$$\overline{p}\!\!\!/_T = E_{\nu_1} \cdot \overline{n}_1 + E_{\nu_2} \cdot \overline{n}_2$$



$\overline{n}_1$, $\overline{n}_2$ - τ jets directions

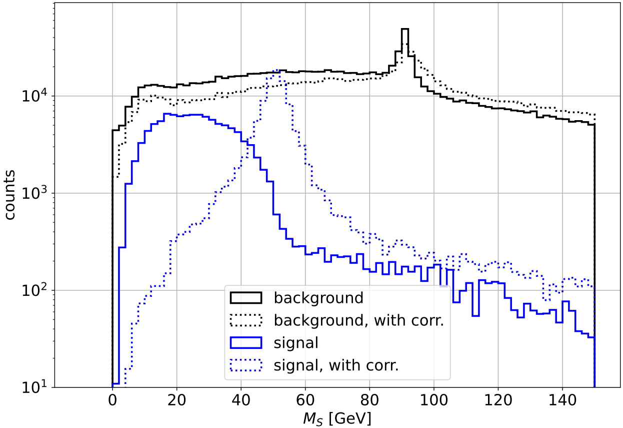
unique solution

works also for semi-leptonic and leptonic events

arXiv:2307.15651

S mass reconstruction

Reconstructed S mass distribution with applied correction



Example for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight** event selection.
Signal for scalar mass of **50 GeV**.

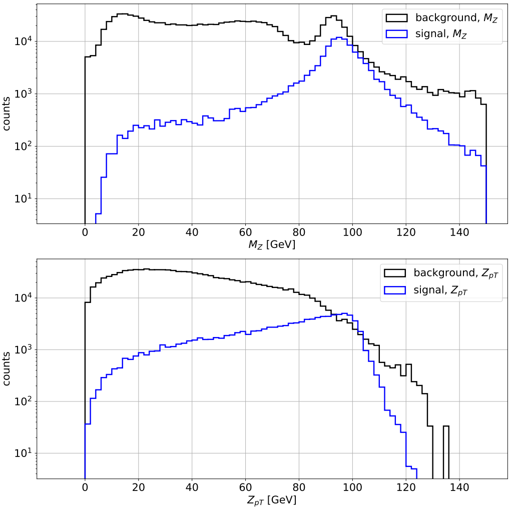
Other variables used for training

Two un-tagged jets taken as Z candidate

Other variables used in classification:

- Z invariant mass
- Z transverse momentum
- recoil mass
- total energy
- y_{23} and y_{34} variables from clustering algorithm
- azimuthal distance of two τ candidates
- polar angle of Z
- τ emission angle in S rest frame

Other variables used for training

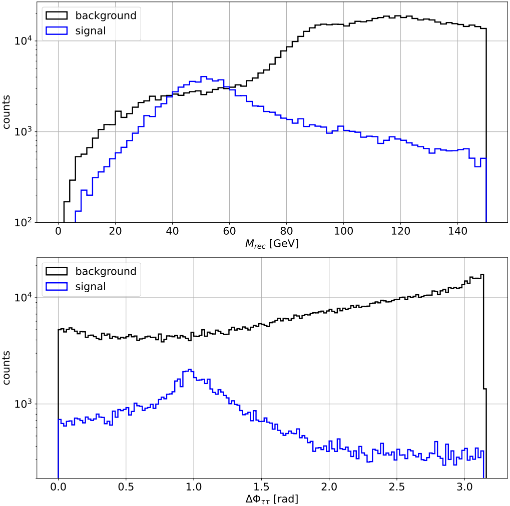


Reconstructed **Z invariant mass** and **transverse momentum** distributions for $\mathbf{e}^-_L\mathbf{e}^+_R$ polarisation,

scalar mass of **50GeV**

and with **tight** selecion

Other variables used for training



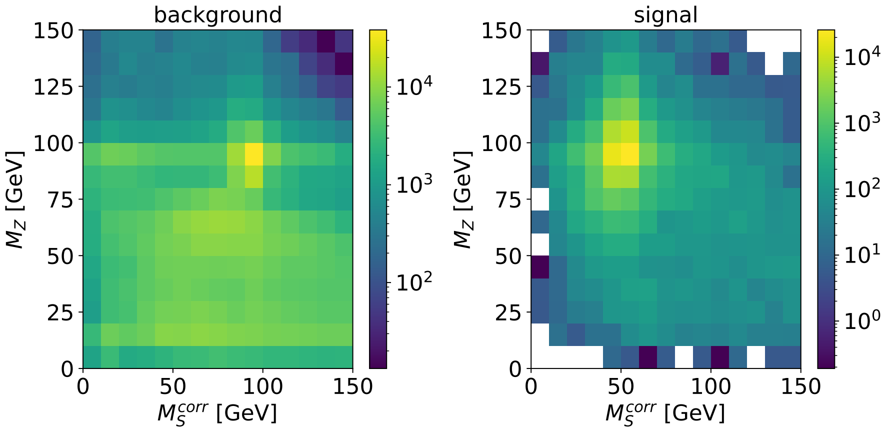
Reconstructed **recoil mass** and **azimuthal distance of two τ candidates** distributions for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation,

scalar mass of **50GeV**

and with **tight** selecion

Signal and background events separation

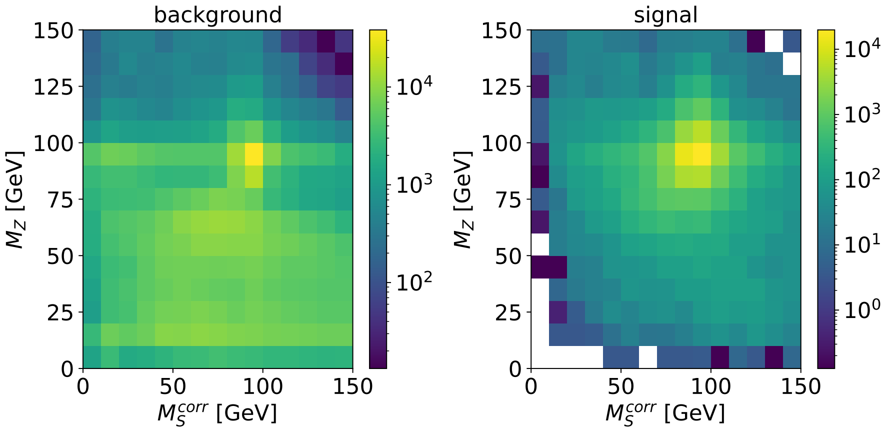
Separation is visible in M_S^{corr} vs M_Z distribution



Example for $\mathbf{e}_L^- \mathbf{e}_R^+$ polarisation and **tight** event selection.
Signal for scalar mass of **50 GeV**.

Signal and background events separation

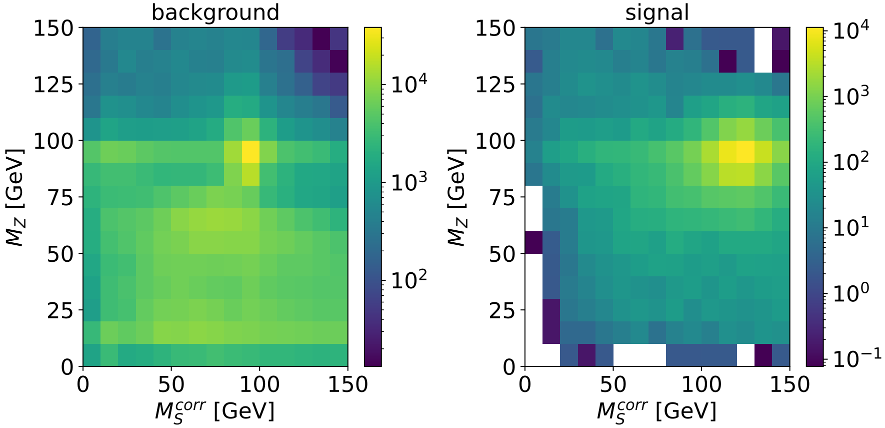
Separation is visible in M_S^{corr} vs M_Z distribution



Example for $\mathbf{e}_L^- \mathbf{e}_R^+$ polarisation and **tight** event selection.
Signal for scalar mass of **90 GeV**.

Signal and background events separation

Separation is visible in M_S^{corr} vs M_Z distribution

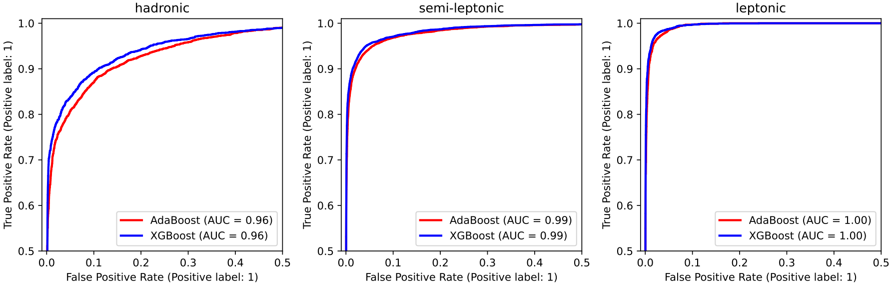


Example for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight** event selection.
Signal for scalar mass of **120 GeV**.

Comparison of classification algorithms

Separate BDT for each polarisation and event category

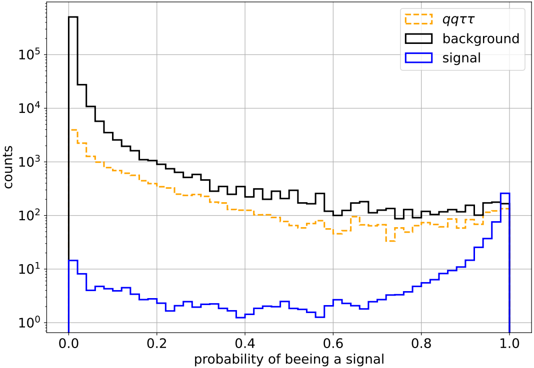
Comparison of AdaBoost and XGBoost classifiers



Example for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight** event selection.
Signal for scalar mass of **50 GeV**.

BDT

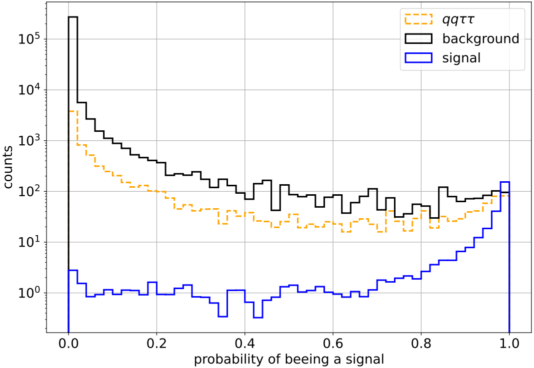
BDT response distribution for signal and background
with dominant $qq\tau\tau$ background



Example for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight semi-leptonic** event selection.
Signal for scalar mass of **50 GeV** normalized to 1% of SM cross section.

BDT

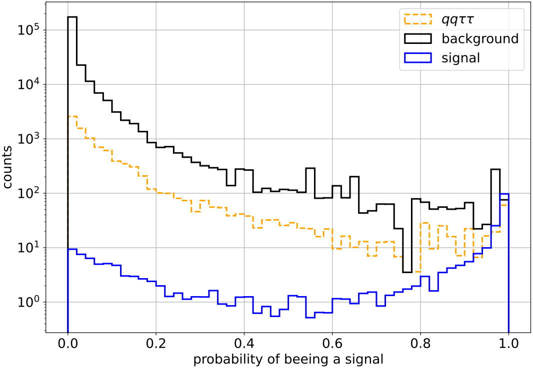
BDT response distribution for signal and background with dominant $qq\tau\tau$ background



Example for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **leptonic** event selection.
Signal for scalar mass of **50 GeV** normalized to 1% of SM cross section.

BDT

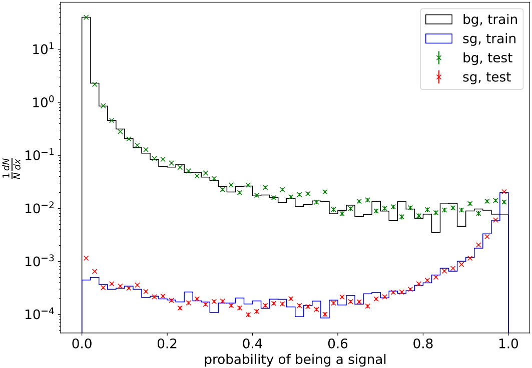
BDT response distribution for signal and background with dominant $qq\tau\tau$ background



Example for $\mathbf{e}^-_L\mathbf{e}^+_R$ polarisation and **tight hadronic** event selection. Signal for scalar mass of **50 GeV** normalized to 1% of SM cross section.

BDT

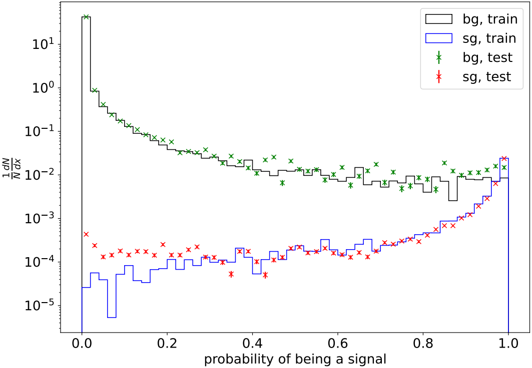
BDT response on training and test data sets (equal size)



Example for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight semi-leptonic** event selection.
Signal for scalar mass of **50 GeV** normalized to 1% of SM cross section.

BDT

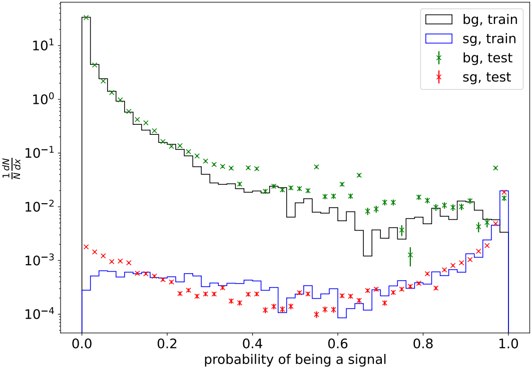
BDT response on training and test data sets (equal size)



Example for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **leptonic** event selection. Signal for scalar mass of **50 GeV** normalized to 1% of SM cross section.

BDT

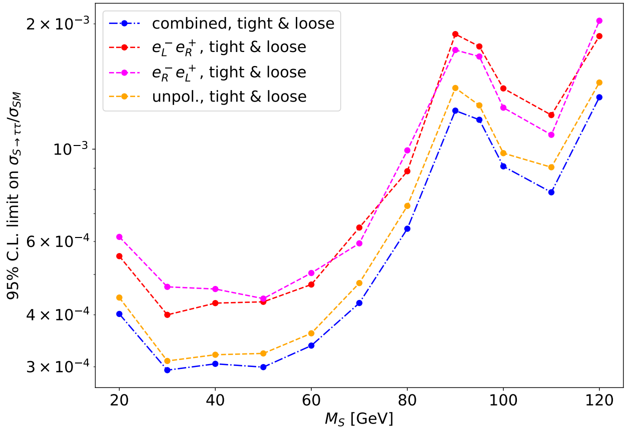
BDT response on training and test data sets (equal size)



Example for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight hadronic** event selection.
Signal for scalar mass of **50 GeV** normalized to 1% of SM cross section.

95% C.L. limits on the production cross section

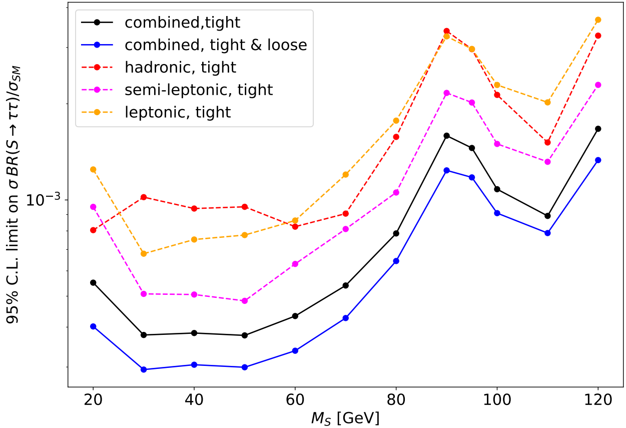
in units of the SM cross section for Higgs-strahlung process (with given scalar mass)



$e_L^- e_R^+$ and $e_R^- e_L^+$ luminosities from ILC H-20 running scenario at 250 GeV

95% C.L. limits on the production cross section

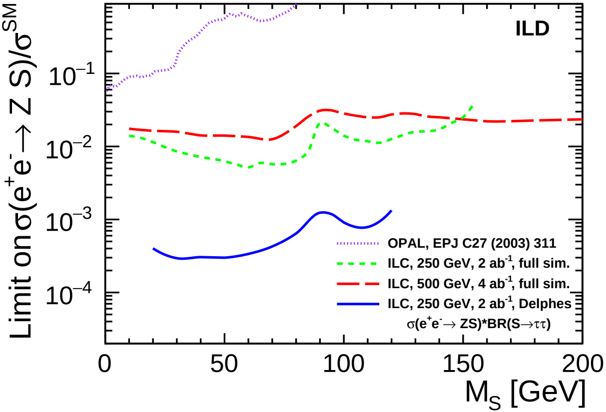
in units of the SM cross section for Higgs-strahlung process
(with given scalar mass)



ILC H-20 running scenario at 250 GeV

95% C.L. limits on the production cross section

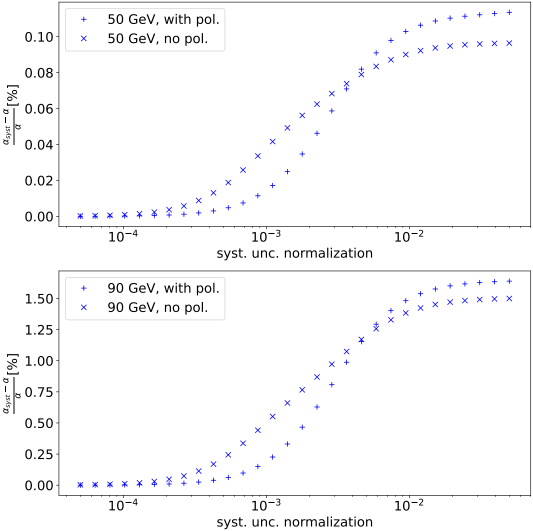
in units of the SM cross section for Higgs-strahlung process
(with given scalar mass)



Limits compared with previous decay mode independent results from ILD

Systematic uncertainties

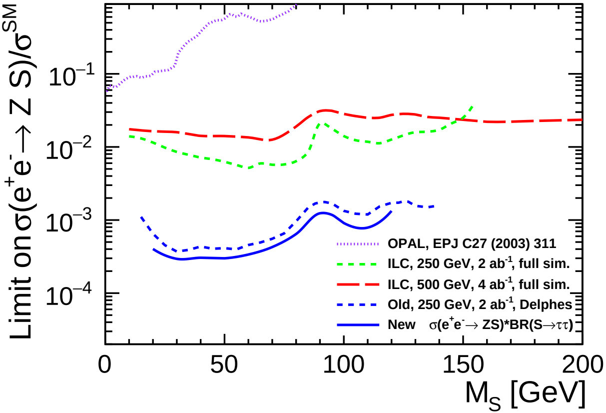
Seven normalization variations (4 lumi and 3 theory) considered.
No significant impact of systematic uncertainties



Conclusions

1. Event selection and reconstruction was applied
2. Correction of jets four-momentum for neutrinos was implemented
3. Boosted decision trees were used for classification
4. **Limits for scalar production cross section were calculated - stronger than previous results**
5. Contribution of different polarisation settings into limits was studied
6. Impact of normalization uncertainties was found to be negligible

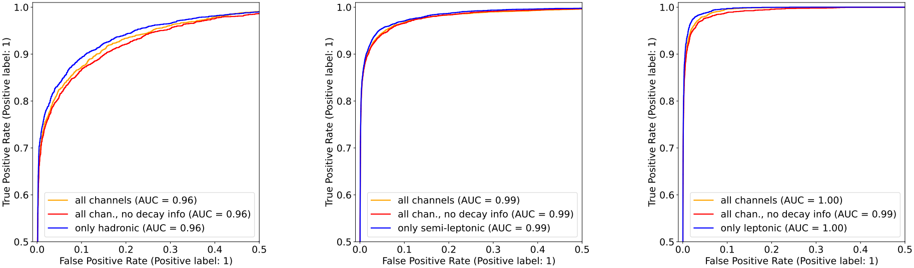
Backup - previous results



Limits compared with results presented on EPS-HEP'2023 conference in Hamburg

Backup - XGBoost ROC curves

Comparison of BDTs trained on different event samples.



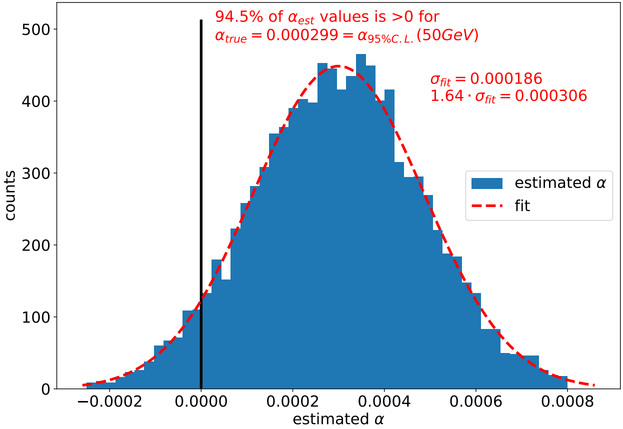
Example for $\mathbf{e}_L^- \mathbf{e}_R^+$ polarisation and **tight** event selection.
Signal for scalar mass of **50 GeV**.

Backup - validation

Expected number of events in ith bin: $\mu_i = b_i + \alpha s_i$

Pseudo-experiments generated for $\alpha = \alpha_{95\% C.L.}(50 GeV)$

Distribution of estimated α values



Backup - formulas

Expected number of events in ith bin:

$$\mu_i = \sum_{i=1}^{N_{bin}} b_i + \alpha s_i$$

Log-likelihood function:

$$l(\alpha) = \sum_{i=1}^{N_{bin}} (n_i \log \mu_i - \mu_i) - \sum_{i=1}^{N_{bin}} n_i!$$

Log-likelihood 1^{st} derivative:

$$\frac{dl}{d\alpha}(\alpha) = \sum_{i=1}^{N_{bin}} \left(\frac{n_i}{\mu_i} - 1 \right) \frac{d\mu_i}{d\alpha} \; (= 0)$$

Log-likelihood 2^{nd} derivative:

$$-\frac{d^2 l}{d\alpha^2}(\alpha) = \sum_{i=1}^{N_{bin}} \frac{n_i}{\mu_i^2} \left(\frac{d\mu_i}{d\alpha} \right)^2 = \sum_{i=1}^{N_{bin}} \frac{s_i^2}{b_i} = \frac{1}{\delta_\alpha^2}, \quad \alpha_{95\% C.L.} = 1.64 \cdot \delta_\alpha$$