# Light Higgs bosons at CEPC - experiment

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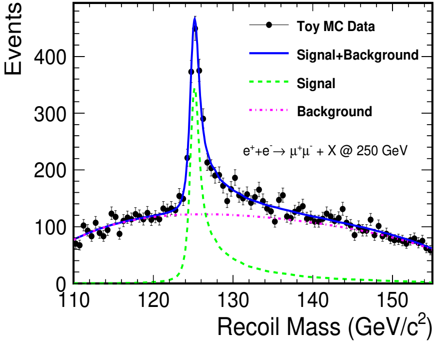
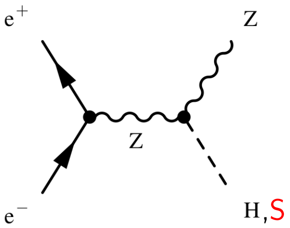
## Light Higgs bosons

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 Higgses / light exotic scalar states is still not excluded by the existing data (!)

as discussed by Tania in the previous presentation...

## ECFA study

Light scalar searches at future Higgs Factories were only partially studied so far.
More work is clearly needed to understand the experimental challenges and prospects.
Light scalar searches were selected as one of the ECFA study focus topics arXiv:2401.07564

# Motivation

## ECFA study

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## 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 also be explored.

## Theoretical and phenomenological targets (2)

Second benchmark scenario: light scalar pair-production in 125 GeV Higgs boson decays

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

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 (there is a dedicated topic focusing on LLPs).

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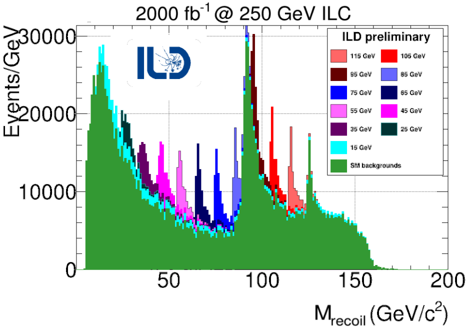
In this talk I will focus on the new activities triggered by the ECFA study on EXscalar focus topic target (1): **direct light Higgs production in the scalar-strahlung process**

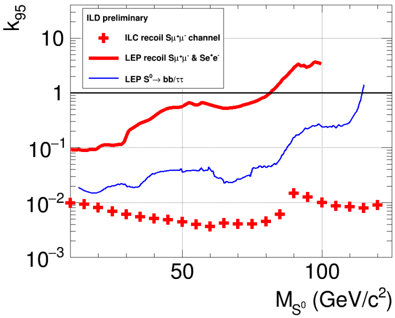
Most studies were carried out in the framework of the ILD concept group
But the results should be quite general, applying to all 240–250 GeV $e^+e^-$ machines...

# Previous studies

## Decay mode independent search

ILD full simulation study    arXiv:1903.01629    arXiv:2005.06265




Reconstructed recoil mass spectra for

$e^+e^- \rightarrow Z\ S^0 \rightarrow \mu^+\mu^- + X$

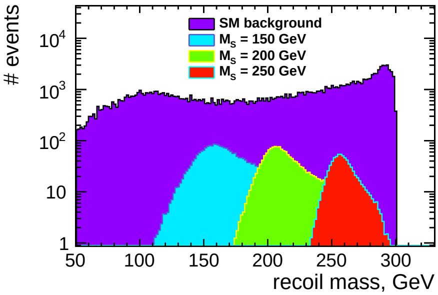
Expected sensitivity
(relative to SM-like Higgs boson production rate)

# Previous studies

## Decay mode dependent search

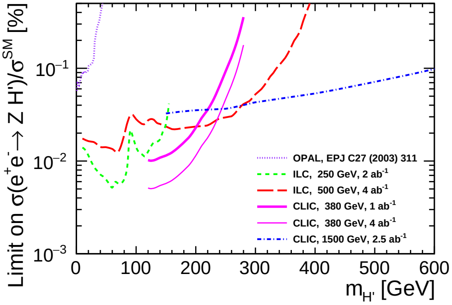
CLIC fast simulation study assuming **invisible scalar decays** arXiv:2002.06034 arXiv:2107.13903

Reconstructed recoil mass spectra




for hadronic $Z$ decays

Expected sensitivities of CLIC

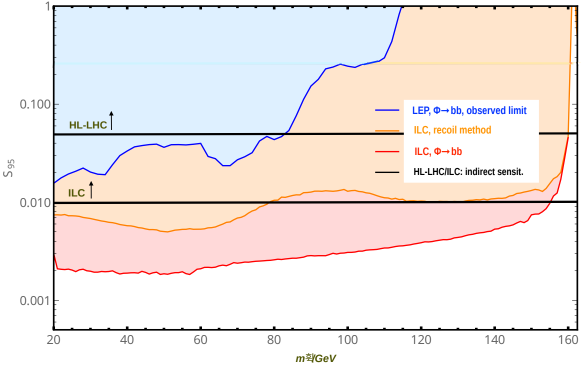



compared with decay independent limits from LEP and ILC

## Decay mode dependent search

Generator level only !

Estimated prospects for new scalar discovery in $S \to b\bar{b}$ decay channel (LEP projection)




Expected 95% C.L. limits on the scalar production cross section $\sigma/\sigma_{SM}$ assuming standard BRs

arXiv:1801.09662

## Decay dependent search

Two decay channels considered at the moment:

- $S \to b\bar{b}$ dominant in SM-like scenarios for $M_s > 10 GeV$
- $S \to \tau^+\tau^-$ enhanced in some of the BSM models

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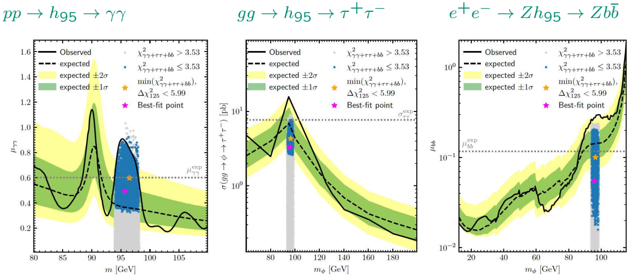
Some of the experimental discrepancies pointed to new scalar with dominant decay to $\tau\tau$...




Sven Heinemeyer @ First ECFA WS on e$^+$e$^-$ Higgs/EW/top factories, October 2022; arXiv:2203.13180

## Event samples

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 estimate.
Contribution from two-fermion and six-fermion processes found to be small.

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

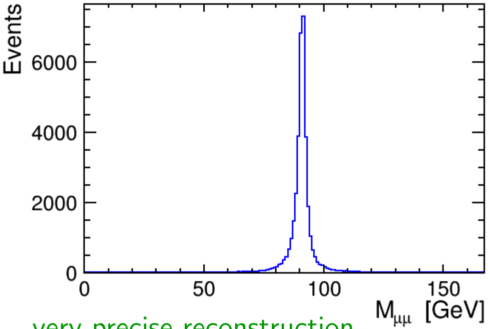
Total lumionsity of $2\,\mathrm{ab}^{-1}$, with $\pm 80\%/\pm 30\%$ polarisation for $\mathrm{e}^-/\mathrm{e}^+$ (H-20 scenario).

Fast detector simulation with Delphes ILCgen model.

## Event reconstruction

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

$Z$ mass from leptonic decays:




very precise reconstruction...

Direct reconstruction of the scalar mass much more problematic. Invariant mass of two $b$ jets poorly reconstructed, large impact of energy losses in semi-leptonic heavy meson decays.

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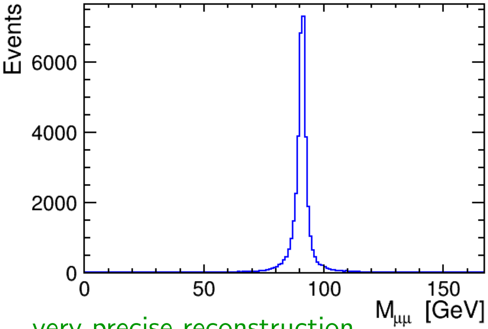


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Direct reconstruction of the scalar mass much more problematic. Invariant mass of two $b$ jets poorly reconstructed, large impact of energy losses in semi-leptonic heavy meson decays.

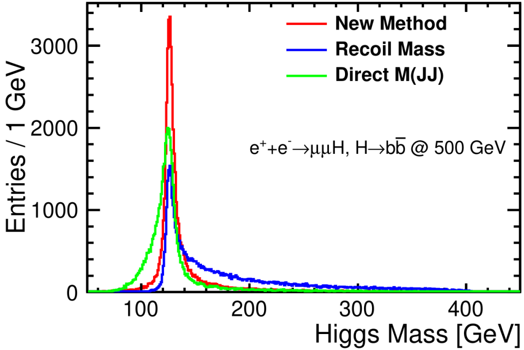
However, conservation of transverse momentum can be used to reconstruct jet energies from leptonic final state and jet angles.

ILD-PHYS-PUB-2019-001

## Event reconstruction

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

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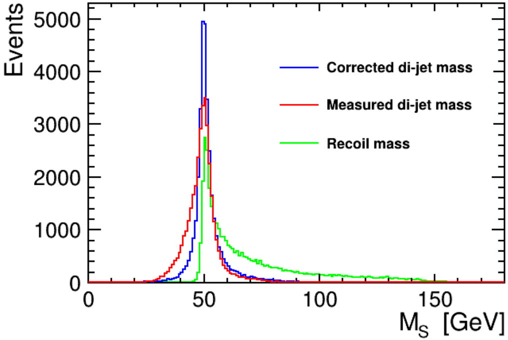
Fast simulation for 50 GeV scalar at 250 GeV

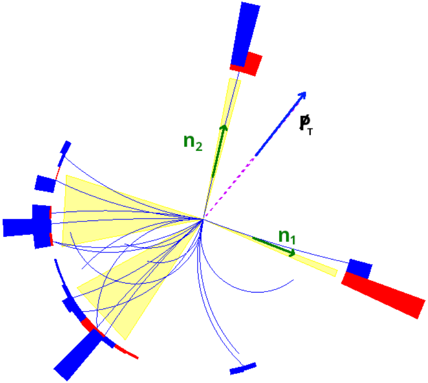



B.Brudnowski, first results, work in progress...

## Event reconstruction

arXiv:1509.01885

Example signal event with hadronic tau decays




Tau leptons are very boosted $\Rightarrow$ collinear approximation

Assume tau neutrinos are emitted in the tau jet direction.

Their energies can be found from transverse momentum balance:

$$\vec{\not{p}}_T = E_{\nu_1} \cdot \vec{n_1} + E_{\nu_2} \cdot \vec{n_2}$$

where $\vec{n_1}$ and $\vec{n_2}$ are directions of the two tau jets.

Unique solution !

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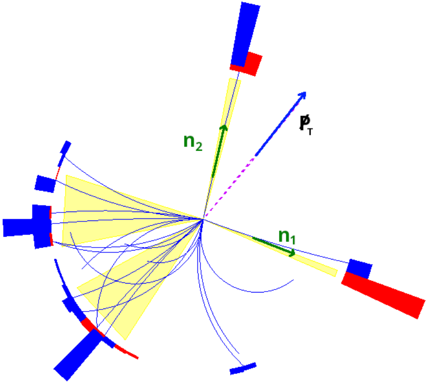


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Unique solution !

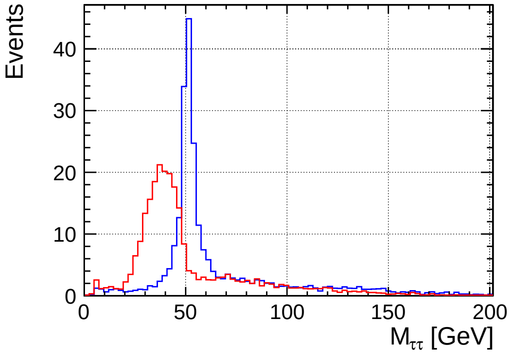
Works also for semi-leptonic and leptonic events!

Because of small tau mass $\Rightarrow$ small invariant mass of neutrino pair

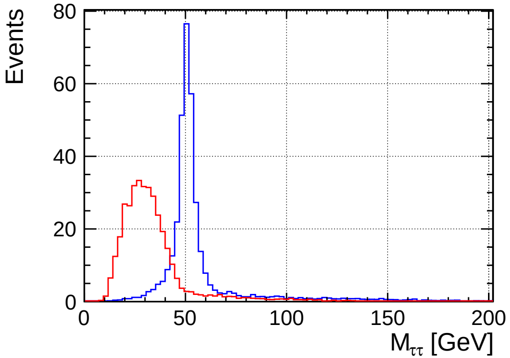
## Event reconstruction

Distribution of the raw and corrected mass of the tau candidate pair for $M_S = 50\,\text{GeV}$

Hadronic events (two tagged jets)



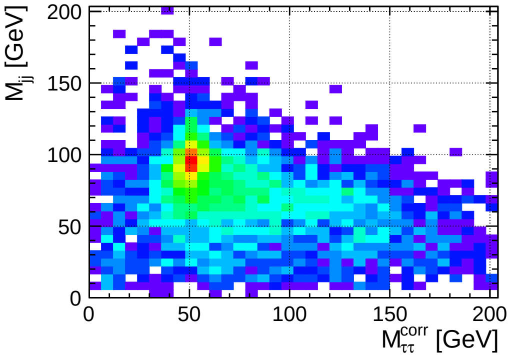

Semi-leptonic events (lepton and one tagged jet)



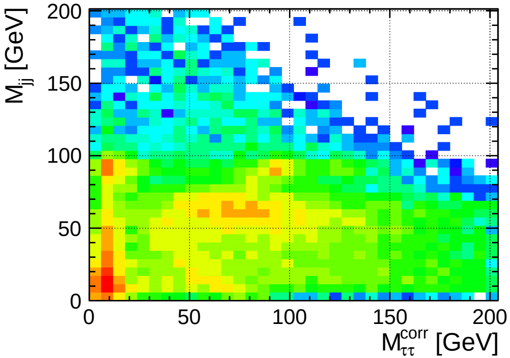
## Kinematic distributions

Distribution of the reconstructed Z boson and scalar masses for $M_S = 50\,\mathrm{GeV}$

Hadronic signal events




Background events

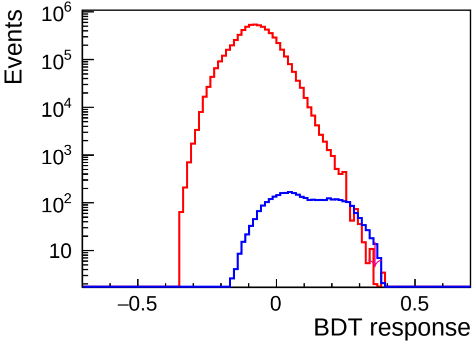


## Final event selection

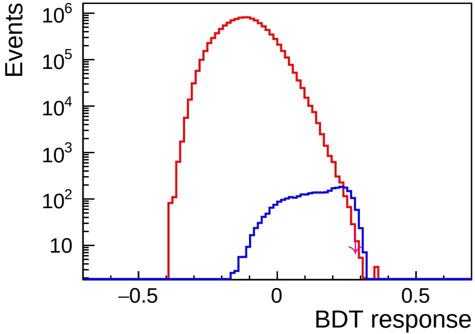
see backup slides for list of BDT input variables

Example of BDT response distribution for signal and background events, for $M_S = 50\,\mathrm{GeV}$

Hadronic events




Semi-leptonic events

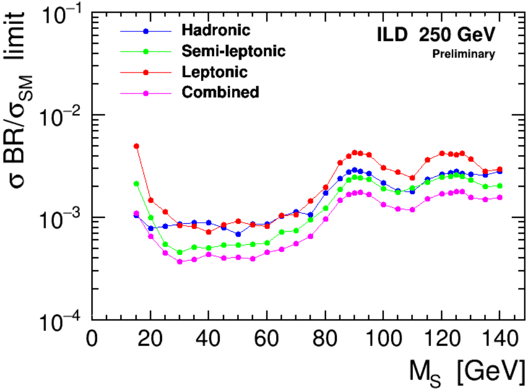



Loose pre-selection, signal normalized to $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)/\sigma_{SM} = 1\%$

## Cross section limits

Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)$

BDT cut optimized for 1% signal level; combined data, polarisation not taken into account!



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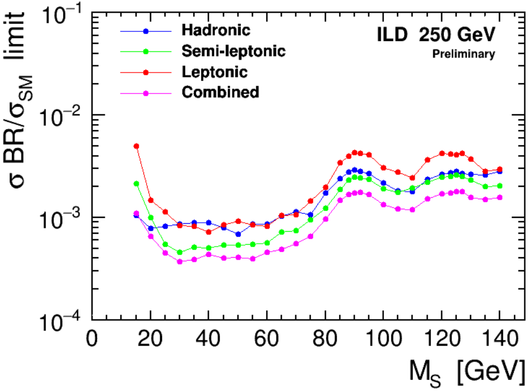


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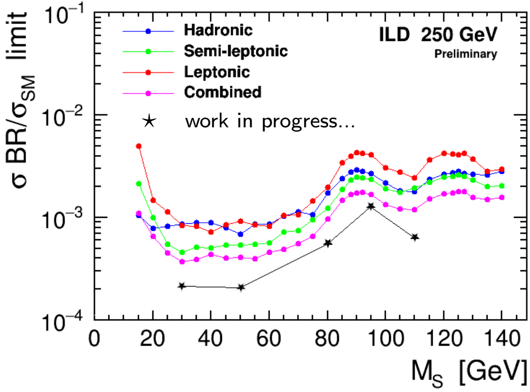


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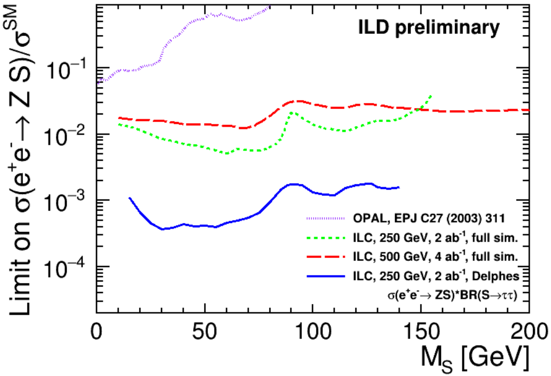
⇐ K.Zembaczynski
work in progress...

## Cross section limits

Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)$
compared with decay independent limits on $\sigma/\sigma_{SM}$ from earlier studies

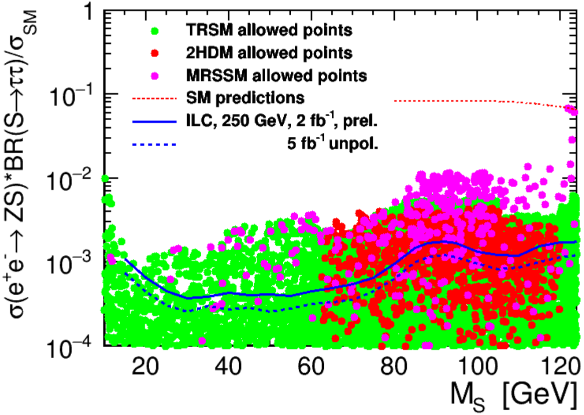



Targeted analysis results in order of magnitude increase in sensitivity...

Possible gain in discovery reach depends on the BR!

## Cross section limits

Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)$
compared with allowed scenarios in different models




Two-Real-Singlet Model
thanks to Tania Robens
see arXiv:2209.10996 arXiv:2305.08595

Two Higgs-Doublet Model
thanks to Kateryna Radchenko
thdmTool package, see arXiv:2309.17431

Minimal R-symmetric Supersymmetric SM
thanks to Wojciech Kotlarski arXiv:1511.09334

# Conclusions

BSM scenarios with light scalars still not excluded by existing data

Sizable production cross sections for new scalars can coincide with non-standard decay...

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**Results for the ECFA study report need to be completed by the end of the year!**
Please let me know, if you would like to contribute to the EXscalar focus topic...

# Thank you!

## ECFA study focus topics

Selected in order to stimulate new engagement and trigger additional activities in areas where further work would be still be beneficial...

arXiv:2401.07564

| | Topic | Lead group | Relevant $\sqrt{s}$ [GeV] 91 | 161 | 240–250 | 350–380 | $\geq 500$ |
|---|---|---|---|---|---|---|---|
| 1 | HtoSS | HTE | | | ✓ | ✓ | ✓ |
| 2 | ZHang | HTE (GLOB) | | | ✓ | ✓ | ✓ |
| 3 | Hself | GLOB | | | ✓ | ✓ | ✓ |
| 4 | Wmass | PREC | | ✓ | ✓ | ✓ | ✓ |
| 5 | WWdiff | GLOB | | | ✓ | ✓ | ✓ |
| 6 | TTthres | GLOB (HTE) | | | | ✓ | ✓ |
| 7 | LUMI | PREC | ✓ | ✓ | ✓ | ✓ | ✓ |
| 8 | EXscalar | SRCH | | | ✓ | ✓ | ✓ |
| 9 | LLPs | SRCH | ✓ | ✓ | ✓ | ✓ | ✓ |
| 10 | EXtt | SRCH | | | | ✓ | ✓ |
| 11 | CKMWW | FLAV | | ✓ | ✓ | ✓ | ✓ |
| 12 | BKtautau | FLAV | ✓ | | | | |
| 13 | TwoF | HTE (PREC) | ✓ | ✓ | ✓ | ✓ | ✓ |
| 14 | BCfrag and Gsplit | PREC (FLAV) | ✓ | ✓ | ✓ | ✓ | ✓ |

## ILC running scenario

The unique feature of the ILC is the possibility of having both electron and positron beams polarised! This is crucial for many precision measurements as well as BSM searches.

Four independent measurements instead of one:

- increase accuracy of precision measurements
- more input to global fits and analyses
- remove ambiguity in many BSM studies
- reduce sensitivity to systematic effects

Integrated luminosity planned with different polarisation settings [fb$^{-1}$]

| **H-20** $\sqrt{s}$ | sgn$(P(e^-), P(e^+))$ $(-,+)$ | $(+,-)$ | $(-,-)$ | $(+,+)$ | Total |
|---|---|---|---|---|---|
| 250 GeV | 900 | 900 | 100 | 100 | 2000 |
| 350 GeV | 135 | 45 | 10 | 10 | 200 |
| 500 GeV | 1600 | 1600 | 400 | 400 | 4000 |

arXiv:1903.01629

## $S \to \tau^+\tau^-$ event selection

Selection based on BDT classifier trained with following input variables:

- measured di-tau mass (before correction)
- corrected di-tau mass (scalar candidate mass)
- measured di-jet mass (Z boson mass)
- recoil mass calculated from Z boson four-momentum
- total event energy (after tau energy correction)
- jet clustering parameter $y_{34}$
- polar angle of the Z boson emission
- decay angles in the scalar rest frame
- azimuthal distance between two tau candidates

## $S \to \tau^+\tau^-$ selection

BDT selection results for **hadronic events** signal hypothesis with $M_S = 50\,\mathrm{GeV}$.
Combined $2\,\mathrm{ab}^{-1}$ of data, polarisation not taken into account.

| Sample | $N_{pres}$ | $N_{BDT}$ | $\varepsilon_{BDT}$ [%] |
|---|---|---|---|
| Signal | 3404 | 823 | 24 |
| $qq\tau\tau$ | 113990 | 725 | 0.64 |
| $qqll$ | 263320 | 70.9 | 0.027 |
| $qqqq$ | 1851500 | 1370 | 0.074 |
| $qq\tau\nu$ | 2509100 | 52.7 | 0.0021 |
| $qql\nu$ | 1381200 | 125 | 0.0091 |
| Total | 6119200 | 2347 | **Sig = 14.6** |

$N_{pres}$ - events expected after pre-selection, $N_{BDT}$ - after BDT response cut, BDT $> 0.2$.

## $S \to \tau^+\tau^-$ selection

BDT selection results for **semi-leptonic events** for signal with $M_S = 50\,\mathrm{GeV}$.
Combined $2\,\mathrm{ab}^{-1}$ of data, polarisation not taken into account.

| Sample | $N_{pres}$ | $N_{BDT}$ | $\varepsilon_{BDT}$ [%] |
|---|---|---|---|
| Signal | 3079 | 999 | 32 |
| $qq\tau\tau$ | 69160 | 860 | 1.2 |
| $qqll$ | 359900 | 152 | 0.042 |
| $qqqq$ | 2213 | 15.1 | 0.68 |
| $qq\tau\nu$ | 1337700 | 79.1 | 0.0059 |
| $qql\nu$ | 9366300 | 43.1 | 0.00046 |
| Total | 11135300 | 1149 | **Sig = 21.6** |

$N_{pres}$ - events expected after pre-selection, $N_{BDT}$ - after BDT response cut, BDT $> 0.2$.