

Update on Exotic scalar searches in $S \rightarrow \tau\tau$ decay channel

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ILD Detector Optimisation Meeting
October 28, 2026

Light scalar searches considered in the ECFA study, selected as focus topic. [arXiv:2401.07564](#)
Results from Delphes level analysis of $S \rightarrow \tau\tau$ (2023-2024) included in ECFA study report.

[arXiv:2506.15390](#)

This study

- dedicated signal samples with $S \rightarrow \tau\tau$ generated for 250 GeV and 550 GeV in Feb. 2026
too few events in this decay channel for existing MC samples (assuming SM-like decays)
- reconstruction procedure developed by Weronika Sobieć for 550 GeV [S&A April 15](#)
- cross section limits extracted for 250 GeV ILC [S&A July 15](#)
- results from analysis extended to 550 GeV [S&A August 26](#)
- Today:
 - ⇒ 550 GeV limits updated with new, larger SM Higgs samples
 - ⇒ first estimates of systematic uncertainties

Monte Carlo samples

Standard MC-2020 SM background samples for 250 GeV:

- Generated with Whizard v2.8.5 and ILC 250 “SetA” beam parameters.
- Detector response simulation (mostly ILD_I5_o1_v02) with DDSim.
- Standard event reconstruction chain based on Marlin.

Large SM background sample production for 550 GeV:

thanks to Bryan Bliewert

- Generated with Whizard v3.1.4/5 and ILC 500 “SetA” beam parameters.
- Detector response simulation with SGV, standard reconstruction with Marlin.
- **Single H_{SM} production not included $\Rightarrow$ only added in September...**

New signal MC samples:

- Generated with Whizard v3.1.5 (thanks to Junping Tian)
- SGV fast detector simulation and reconstruction (thanks to Mikael Berggren)

All events generated in pure helicity states (100% beam polarisation) and properly mixed.

Reconstruction and pre-selection

same procedure for 250 GeV / 550 GeV

Dedicated high-level event reconstruction in Marlin, based on standard ILCsoft processors.

Reconstruction based on 'PandoraPFOs' collection:

- Isolated photons, leptons and tau jets were identified with corresponding processors (`IsolatedPhotonTagging`, `IsolatedLeptonTagging`, `TaJetClustering`)
- all PFOs, except for isolated photons, clustered into 4 jets (Durham alg., exclusive mode)
- isolated leptons and tau jet candidates linked to Durham jets

Events with multiple isolated photons, hard colinear photons or missing p_Z removed (Z return)

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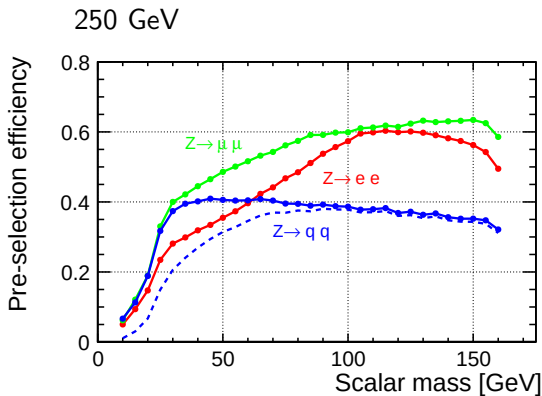
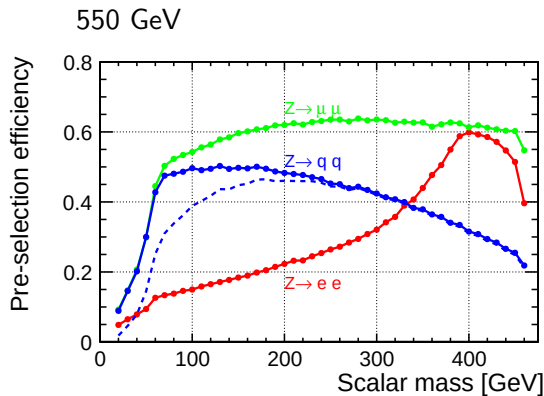
`Z decay` channel is identified first:

- events with two massive jets ($M_{j_1} > 5/8$ GeV, $M_{j_2} > 3$ GeV) considered hadronic Z decays
- otherwise pair of leptons matching M_Z (60–140 GeV) required for leptonic Z decay

`Scalar decay`: two tau candidates (`isolated leptons or tau jets`) required – “tight selection” (!)

Signal pre-selection efficiency

All tau decay channels included: (dashed: without merged tau jets)



Pre-selection efficiency for $Z \rightarrow e^+ e^-$ biased by the contribution from ZZ fusion channel

Background pre-selection

Expected SM background contributions for the combined runs:

Background category	Expected events	
	$2 \text{ ab}^{-1} @ 250 \text{ GeV}$	$4 \text{ ab}^{-1} @ 550 \text{ GeV}$
2f	589'000	2'630
4f	736'000	771'000
6f	80	2'180
SM Higgs	25'800	36'500
Total BG	1'350'000	812'000
50 GeV/250 GeV signal*	4'200 / –	770 / 480

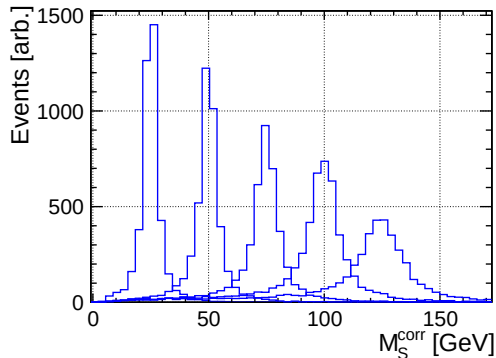
* for 1% of SM cross section at this mass

Scalar mass reconstruction

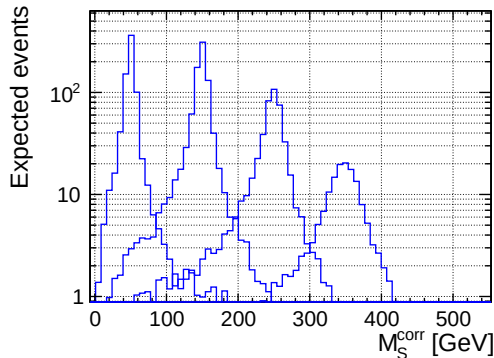
neutrino energies from collinear approximation

Example distributions of corrected mass:

Scalar masses of 25 to 125 GeV at 250 GeV



Scalar masses of 50 to 350 GeV at 550 GeV



All tau decay channels combined

BDT input variables

Event classification using BDT (from root TMVA) with following input variables:

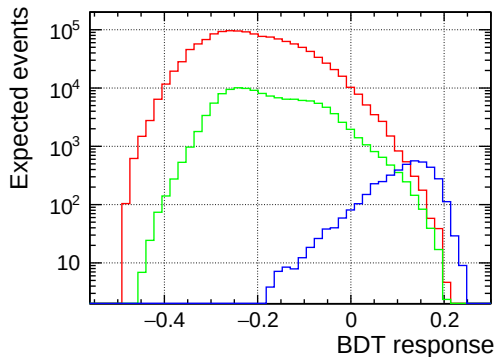
- reconstructed mass of Z candidate (di-lepton or di-jet) and recoil mass
- measured invariant mass of S candidate (di-tau) and corrected S mass
- polar angle of Z candidate, azimuthal angle distance between tau candidates
- scalar decay angles in its CMS
- minimum and maximum distances for PFO clustering into four jets
- total reconstructed energy and energy of ISR photon
- flags indicating decay channels (for Z and two taus) and event class

See backup slides for variable distributions

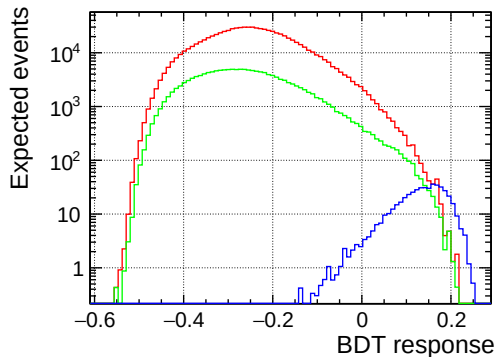
BDT response distribution

Example of BST response distribution: total SM bg., semi-leptonic ZZ, signal.

50 GeV scalar at 250 GeV



250 GeV scalar at 550 GeV

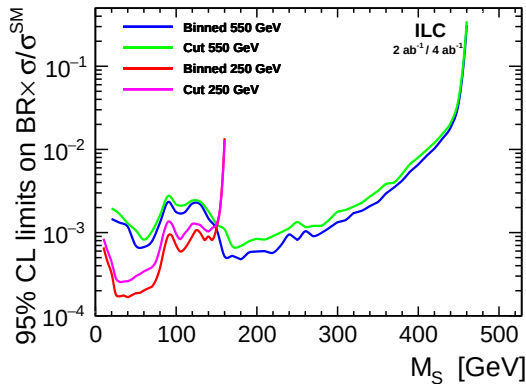


Signal of normalized to 1% of SM cross section for given mass

August'2026 results

Signal samples generated for $M_S=125$ GeV used as (part of) H_{SM} background

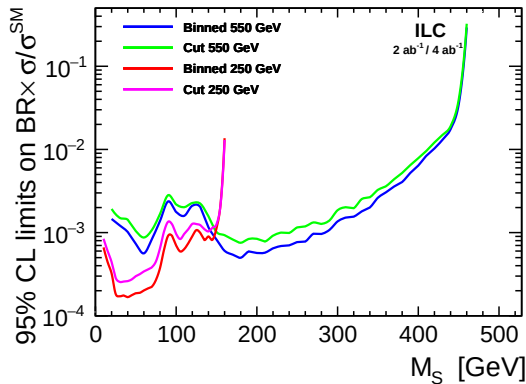
Final limits calculated from the BDT response histogram for signal and background



Updated results

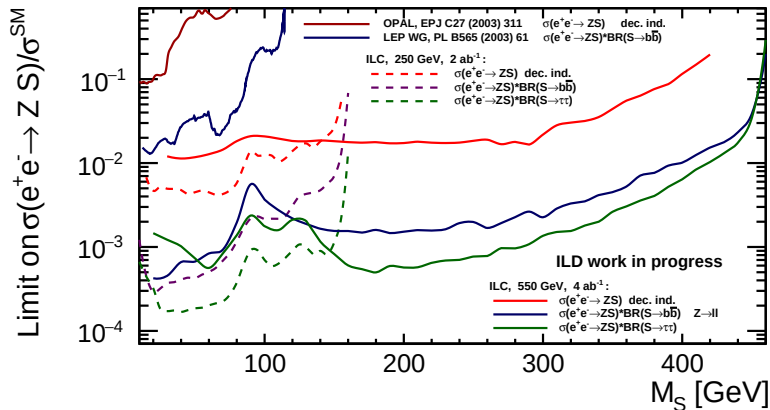
New (larger and more complete) H_{SM} samples included in 550 GeV analysis.

Final limits calculated from the BDT response histogram for signal and background



Updated results

Comparison of all recent ILD results from full simulation / SGV



Limits around $m_S = 125 \text{ GeV}$

Our searches are focused on experimental signatures, with minimal model assumptions. Still, background was calculated as predicted by the SM, including SM Higgs boson.

SM Higgs boson gives significant background contribution for $m_S \sim 125 \text{ GeV}$!

Limits were calculated assuming negligible uncertainty on SM predictions for H_{SM} production!

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But what about so called “sum rule”?

In models with extended scalar sector, scalar couplings to Z boson need to fulfill condition:

$$\sum_i g_{h_i VV}^2 = g_{SM}^2$$

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But what about so called “sum rule”?

If the two scalar states are degenerate in mass, sum of their production cross sections:

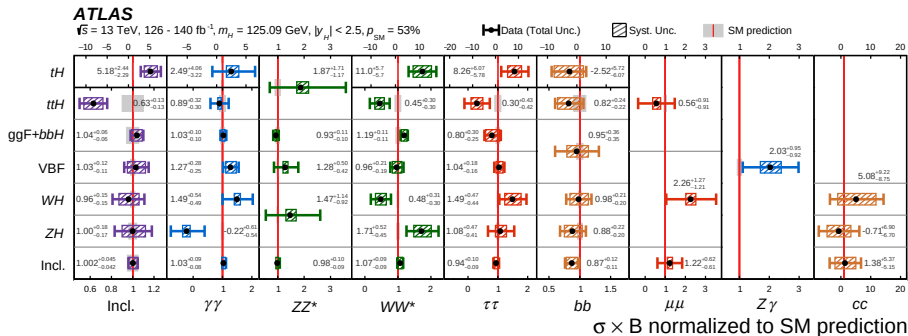
$$\sigma(e^+e^- \rightarrow Z S) + \sigma(e^+e^- \rightarrow Z h_{125}) \approx \sigma^{SM}$$

so no excess is expected production, could only be due to different decay channels...

How should one calculate / present limits for scenarios with scalar mass close to 125 GeV ?!

ATLAS Legacy Run 2 Higgs Combination

arXiv:2608.07332



The uncertainty on the inclusive h_{125} production times di-tau branching ratio is 10%

⇒ take it as the systematic uncertainty on the SM Higgs background normalisation

Cross section limits from BDT histogram

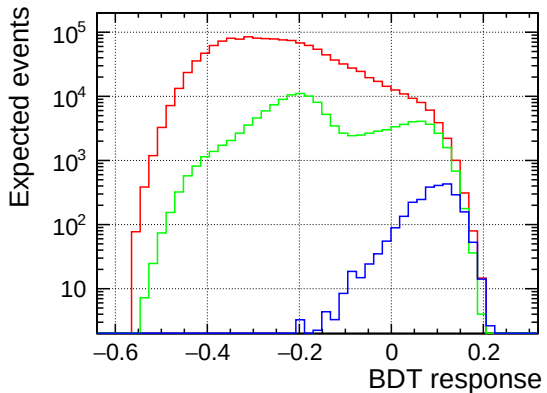
Limits are extracted from the “template fit” to the BDT response histogram:

$$\frac{\delta\sigma}{\sigma_{ref}} = \left(\sum_{i \in bins} \frac{s_i^2}{b_i} \right)^{-\frac{1}{2}}$$

corresponds to combined signal significance in $S \ll B$ limit

where b_i is the number of expected SM background events in each bin and s_i is the number of expected signal events assuming production cross section

$$\sigma_{ref} = 0.01 \cdot \sigma^{SM} \Big|_{m_h=m_S}$$



$M_S = 95 \text{ GeV at } 250 \text{ GeV}$

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Impact of systematic uncertainties can be taken into account as additional nuisance parameters in the fit:

$$\mu_i = b_i + \frac{\sigma}{\sigma_{ref}} \cdot s_i + \sum_{k=1}^{N_{syst}} \Delta_{ki} \cdot \delta_k$$

where Δ_{ki} describes change of SM background in bin i under unit variation of systematic uncertainty k

Cross section limits

Assumed systematic uncertainties:

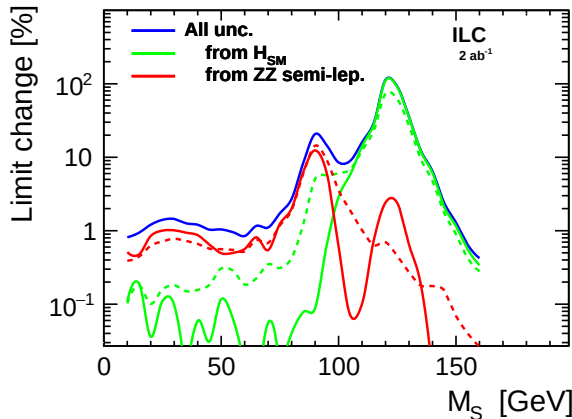
- 10% on H_{SM} contribution
- 0.5% for 2f normalisation
- 1% for each 4f channel

⇒ largest impact from semi-leptonic ZZ
(dominant background)

- 2% for 6f predictions
- 0.1% for luminosity in each polarisation (negligible)

⇒ total of 14 nuisance parameters in the fit

Impact at 250 GeV:



Cross section limits

Assumed systematic uncertainties:

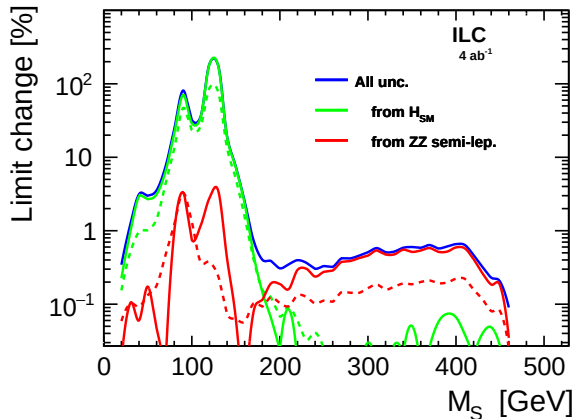
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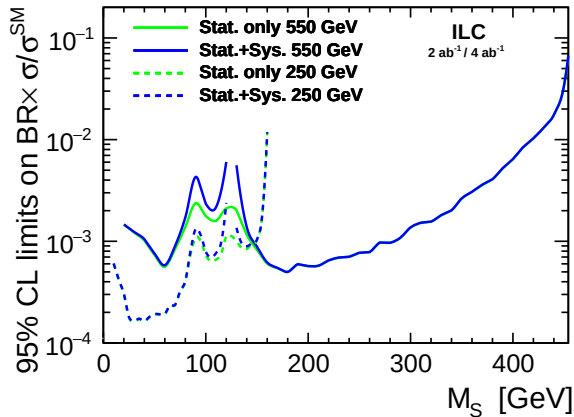
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Impact at 550 GeV:



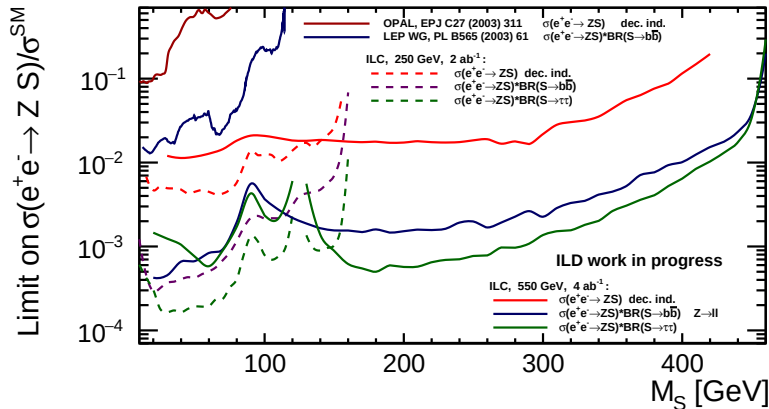
Cross section limits

Comparison of statistical only limits with those including systematic uncertainties



Cross section limits

Comparison with other (stat. only) ILD results from full simulation / SGV



Probably too confusing (stat. vs stat.+sys.) to be shown at LCWS'2026 (?)

Conclusions

Limits from full simulation/SGV analysis of exotic scalar searches in $S \rightarrow \tau\tau$ channel.

Leading background contribution from ZZ events ($qq\tau\tau$ and $\ell\ell\tau\tau$)
and SM Higgs boson production with di-tau decays - irreducible backgrounds

Updated limits with new high statistic SM Higgs background samples included

With 550 GeV data limits at 10^{-3} level extended up to masses of about 300 GeV

Limits on $\sigma \times \text{BR}$ factor 2-3 stronger than for $S \rightarrow b\bar{b}$

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Significant impact of the assumed uncertainty on the SM Higgs boson contribution.

Visible impact also from the 4f normalisation uncertainty

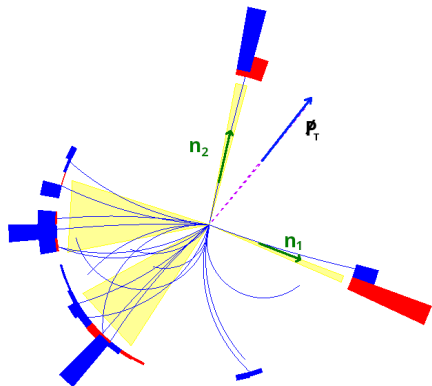
New $S \rightarrow \tau\tau$ results intended for presentation at LCWS'2026

Thank you!

Scalar mass correction

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:

$$\vec{p}_T = E_{\nu_1} \cdot \vec{n}_1 + E_{\nu_2} \cdot \vec{n}_2$$

where $\vec{n}_1$ and $\vec{n}_2$ are directions of the two tau jets.

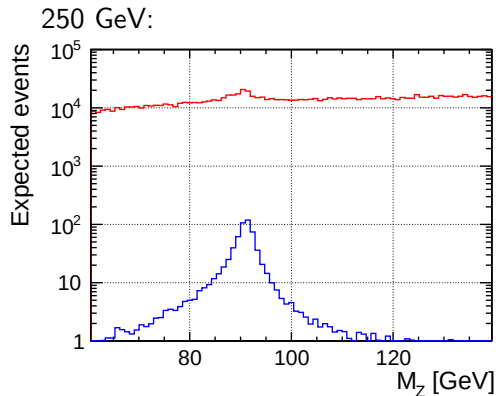
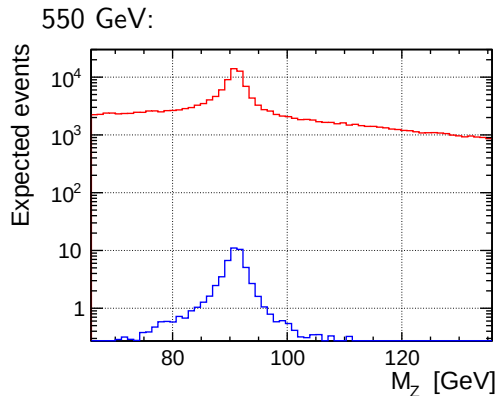
Unique solution !

Works also for semi-leptonic and leptonic events!

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

BDT input variables

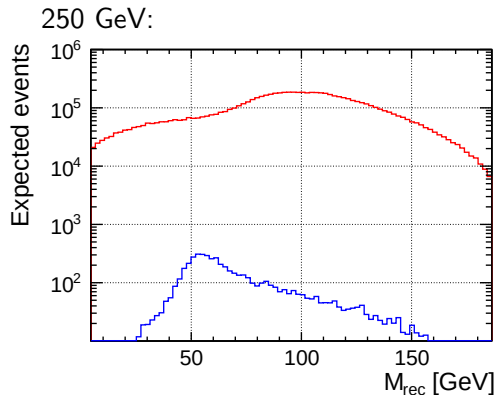
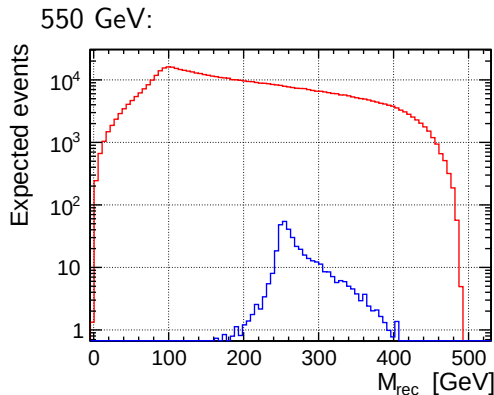
Signal and **SM background** distributions: Z candidate mass in leptonic Z decays.



Signal of 50 GeV / 250 GeV scalar production normalized to 1% of SM cross section

BDT input variables

Signal and **SM background** distributions: recoil mass for hadronic Z decays.

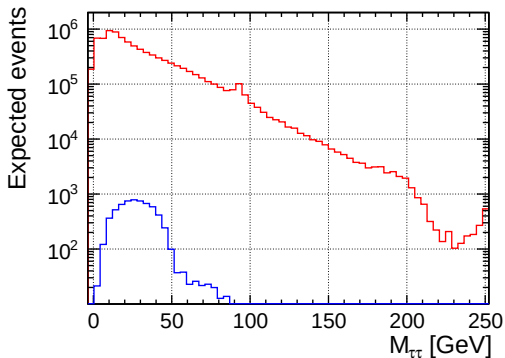


Signal of 50 GeV / 250 GeV scalar production normalized to 1% of SM cross section

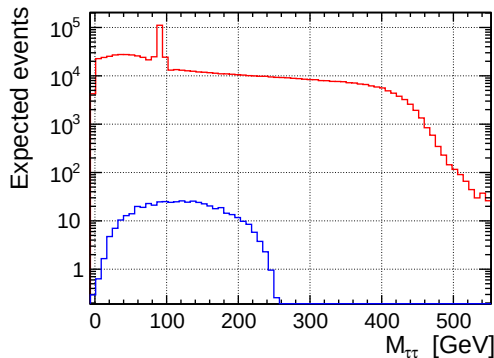
BDT input variables

Signal and **SM background** distributions: raw scalar mass, all Z decays.

250 GeV:



550 GeV:

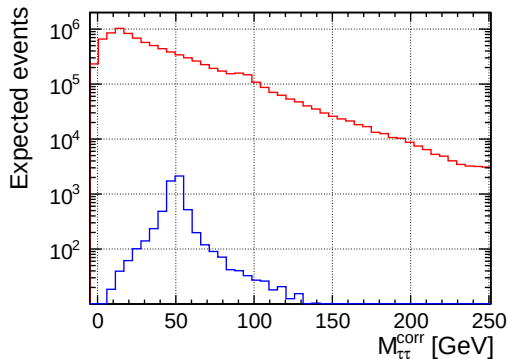


Signal of 50 GeV / 250 GeV scalar production normalized to 1% of SM cross section

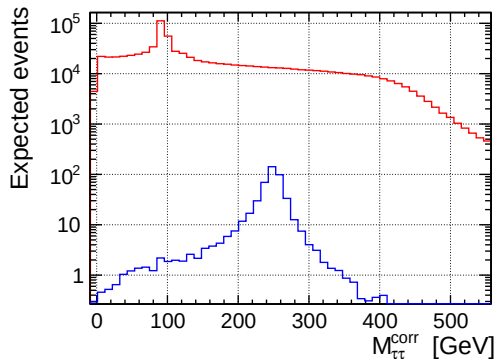
BDT input variables

Signal and **SM background** distributions: corrected scalar mass, all Z decays.

250 GeV:



550 GeV:

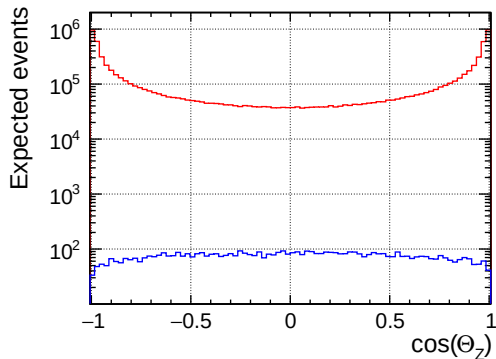


Signal of 50 GeV / 250 GeV scalar production normalized to 1% of SM cross section

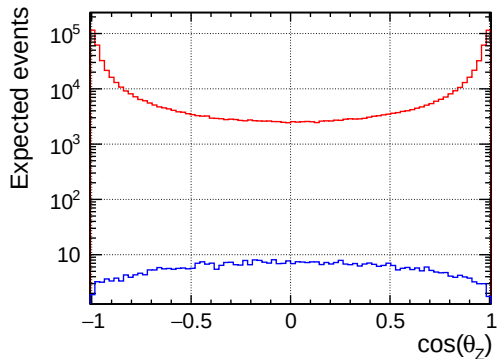
BDT input variables

Signal and **SM background** distributions: Z candidate polar angle

250 GeV:



550 GeV:

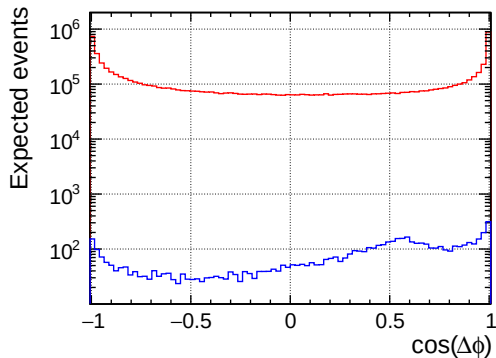


Signal of 50 GeV / 250 GeV scalar production normalized to 1% of SM cross section

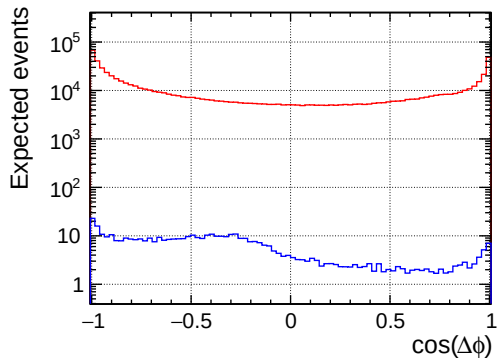
BDT input variables

Signal and **SM background** distributions: azimuthal angle between tau candidates

250 GeV:



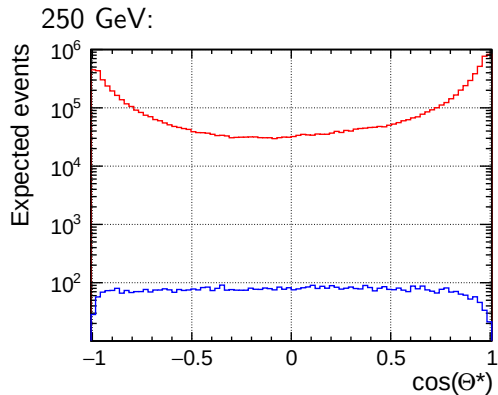
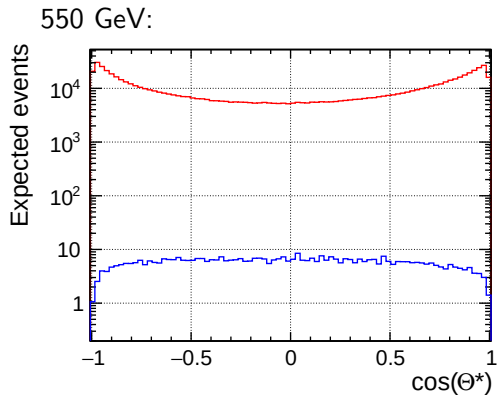
550 GeV:



Signal of 50 GeV / 250 GeV scalar production normalized to 1% of SM cross section

BDT input variables

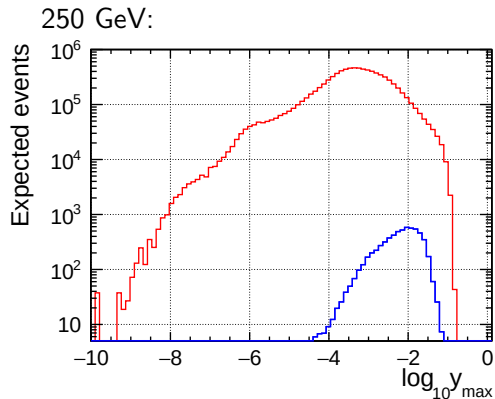
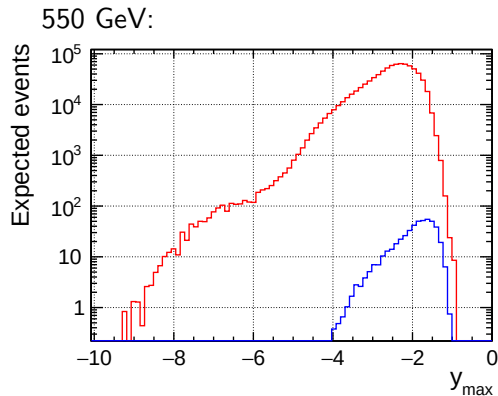
Signal and **SM background** distributions: scalar decay angle (in CMS)



Signal of 50 GeV / 250 GeV scalar production normalized to 1% of SM cross section

BDT input variables

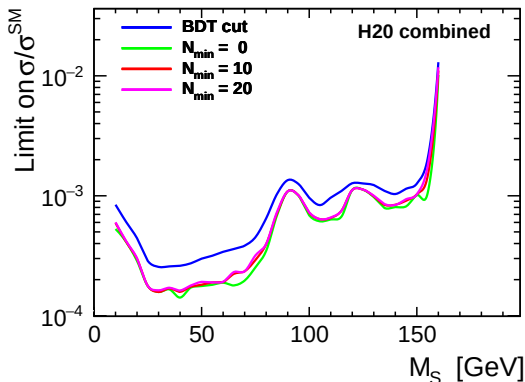
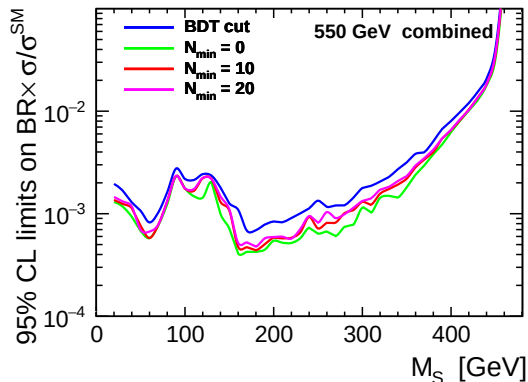
Signal and **SM background** distributions: clustering parameter



Signal of 50 GeV / 250 GeV scalar production normalized to 1% of SM cross section

Cross section limits from BDT histogram

Compared to BDT cut method, limits improve by 20–40%:

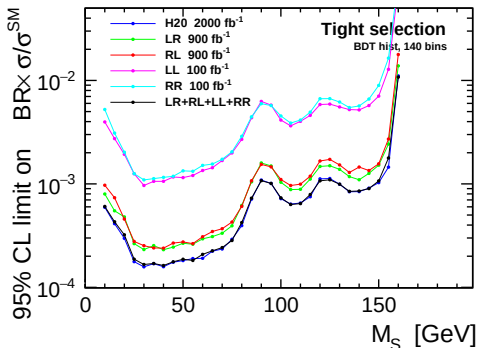


Stable results of re-binning procedure, largely suppressing fluctuations visible for $N_{\text{min}} = 0$

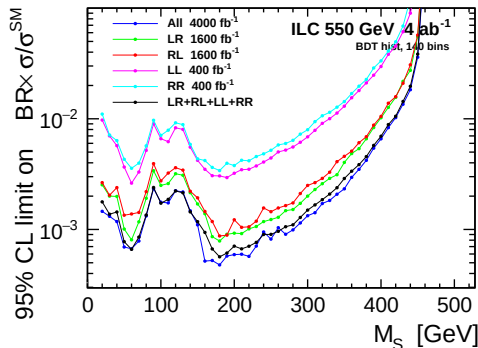
Comparison of limits: Beam polarisation August 2026

Results presented so far were obtained when combining data with different beam polarisation

250 GeV running



550 GeV running

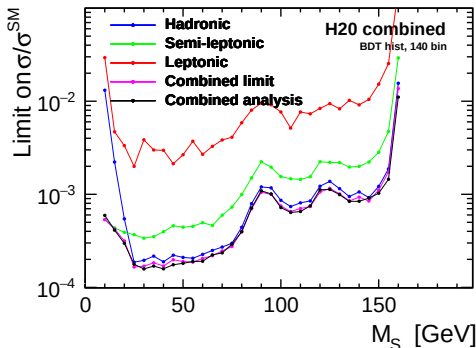


No improvement from combining limits calculated separately for each polarization!

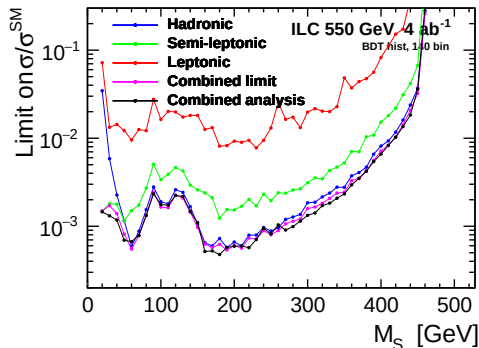
Comparison of limits: tau decays August 2026

Results presented so far were obtained from all tau decay channels combined.

250 GeV running



550 GeV running

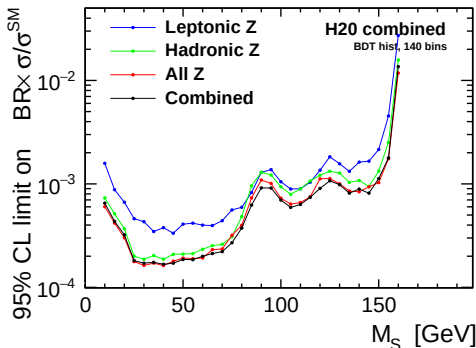


No improvement from combining limits calculated separately for each event type!

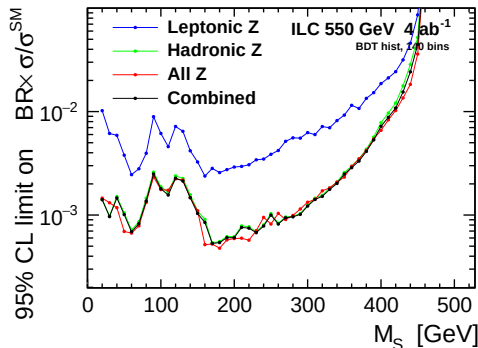
Comparison of limits: Z decays August 2026

Results presented so far were obtained from all Z decay channels combined.

250 GeV running



550 GeV running



Small improvement from combining limits from hadronic and leptonic Z decay only at 250 GeV.