Cross section limits for $e^+e^- \rightarrow Z\,S$ in $S \rightarrow \tau\tau$ channel at 250 GeV ILC

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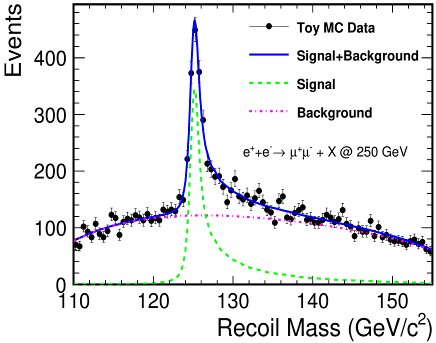
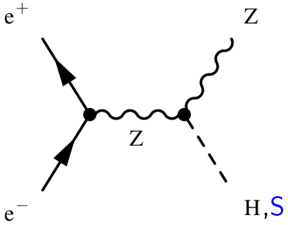
ILD Software and Analysis meeting
July 15, 2026

Motivation

Precision studies of the SM-like Higgs boson will clearly be the main focus at 250 GeV



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



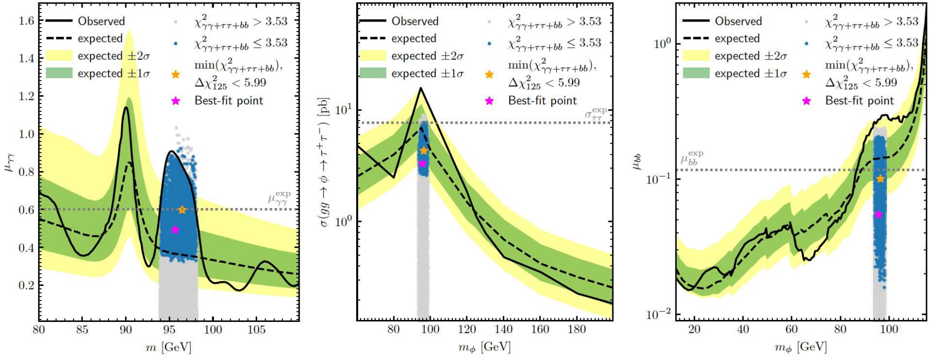
Allowed production cross sections up to $\sim 10\%$ of $\sigma_{SM}(M_S)$

Why $S \to \tau\tau$?

T. Biekötter, S.Heinemeyer, G. Weiglein arXiv:2203.13180

Some discrepancies point to new scalar with mass of ∼95 GeV and dominant decay to $\tau\tau$...

$pp \to h_{95} \to \gamma\gamma$ $\quad$ $gg \to h_{95} \to \tau^+\tau^-$ $\quad$ $e^+e^- \to Zh_{95} \to Zb\bar{b}$



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

Some history

Light scalar searches selected as one of the ECFA study focus topics arXiv:2401.07564

- Delphes level analysis targeting 95 GeV scalar in $S \to \tau\tau$ decay channel
  $\Rightarrow$ results presented at LCWS'2023
- more detailed Delphes study for 20 – 120 GeV mass, combining different event categories
  $\Rightarrow$ finalized for LCWS'2024 and ICHEP'2024 by Kamil Zembaczyński (M.Sc. thesis)
  also contributed to ECFA study report and LC Vision submission

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  also contributed to ECFA study report and LC Vision submission
- dedicated signal samples with $S \to \tau\tau$ generated for 250 GeV and 550 GeV
  too few events in this decay channel for existing MC samples (assuming SM-like decays)
- reconstruction procedure developed by Weronika Sobień for 550 GeV (see S&A April 15)
- same approach applied now to 250 GeV (first results presented on S&A June 17)

Monte Carlo samples

Standard MC-2020 SM background samples:

- Generated with Whizard v2.8.5 and ILC 250 "SetA" beam parameters.
- Detector response simulation (mostly ILD_l5_o1_v02) with DDSim.
- Standard event reconstruction chain based on Marlin.

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), properly mixed to match considered running scenarios.

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

Reconstruction and pre-selection

Final event reconstruction and pre-selection 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

Event reconstruction

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Z decay channel is identified first:

- events with two massive jets ($M_{j_1} > 5$ 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

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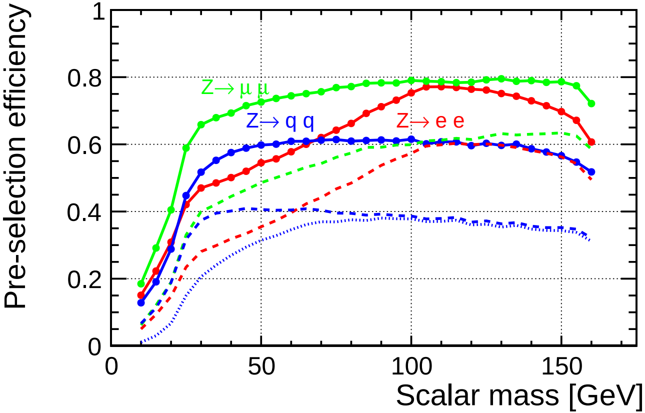
Tau candidates: isolated leptons or tau jets

- two candidates required for “tight selection”
- one candidate and light untagged jet ($M_j < 5$ GeV) required for “loose selection”
- events with no tau candidates removed

Signal pre-selection efficiency

All tau decay channels included: (dashed: tight selection, dotted: merged taus)



Background pre-selection

Expected background contributions for the combined H20 runs at 250 GeV (2 ab^{-1})

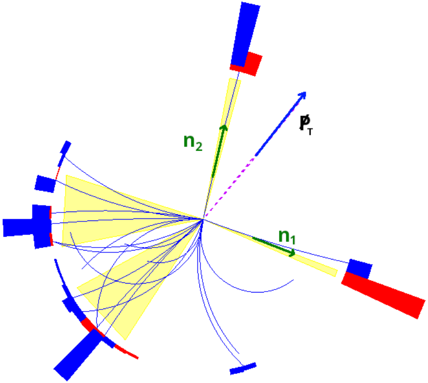
Background category	Event selection: Loose	Event selection: Tight
2f	4'420'000	589'000
4f	4'410'000	736'000
6f	94	80
SM Higgs	35'100	25'800
Total BG	8'870'000	1'350'000
50 GeV signal*	6240	4220

* for 1% of SM cross section at this mass

Scalar mass correction

arXiv:1509.01885

Example signal event with hadronic tau decays



Tau leptons are very boosted ⇒ 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.

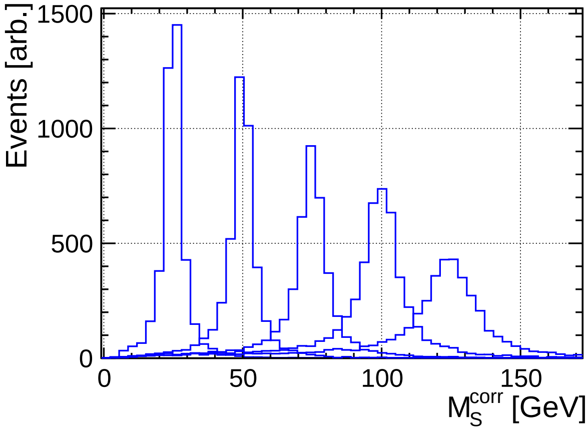
Unique solution !

Works also for semi-leptonic and leptonic events!

Because of small tau mass ⇒ small invariant mass of neutrino pair

Mass correction

Corrected mass distribution for scalar masses of 25, 50, 75, 100 and 125 GeV.



All tau decay channels combined, tight selection

BDT input variables

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

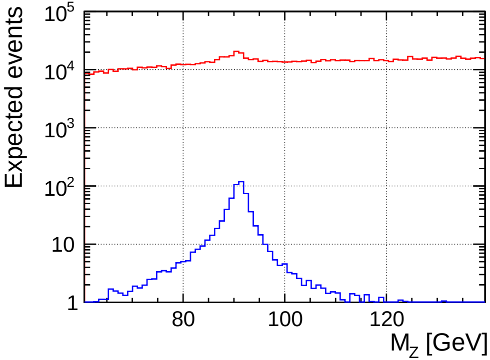
- reconstructed mass of Z candidate (di-lepton or di-jet) and recoil mass
- measured invariant mass of S candidate (di-tau) and corrected S mass
- polar angle of Z candidate, asimuthal angle distance between tau candidates
- scalar decay angles in its CMS
- minimum and maximum distances for PFO clustering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

Event classification

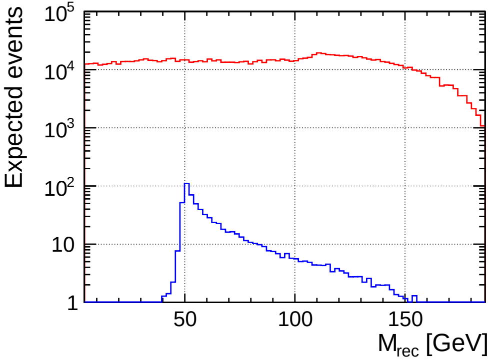
BDT input variables

Signal and **SM background** event distributions, events with leptonic Z decays.

Z candidate mass:



Recoil mass:

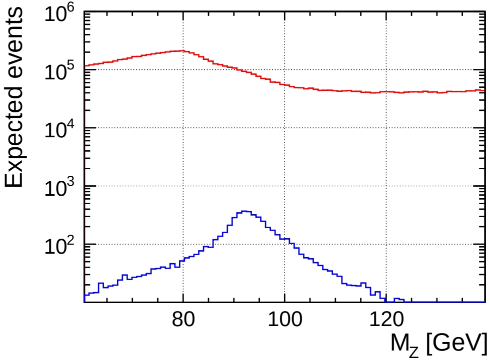


Signal of 50 GeV scalar production normalized to 1% of SM cross section

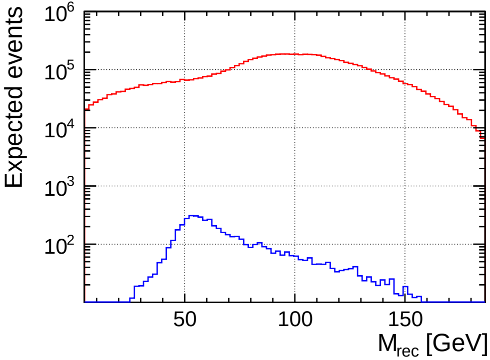
BDT input variables

Signal and **SM background** event distributions, events with hadronic Z decays.

Z candidate mass:



Recoil mass:

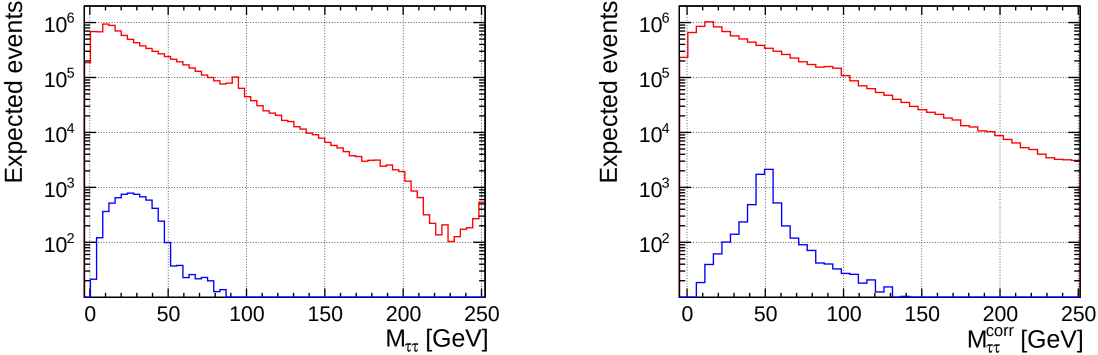


Signal of 50 GeV scalar production normalized to 1% of SM cross section

BDT input variables

Signal and **SM background** event distributions, all Z decays.

Raw scalar mass: Corrected scalar mass:

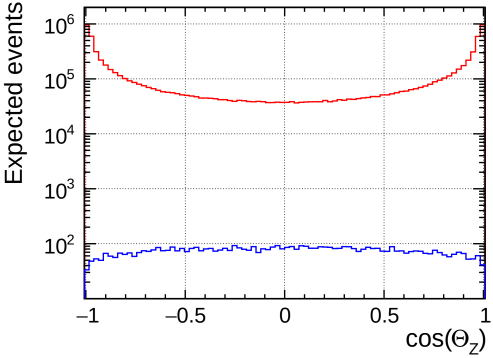


Signal of 50 GeV scalar production normalized to 1% of SM cross section

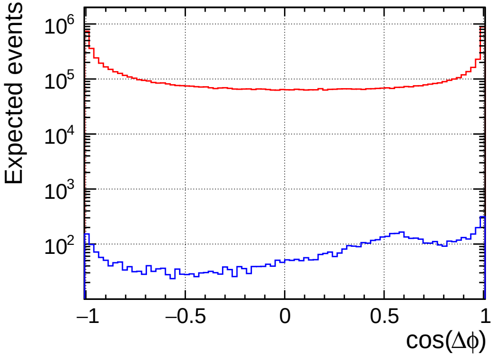
BDT input variables

Signal and **SM background** event distributions, all Z decays.

Z candidate polar angle:



Angle between tau candidates:

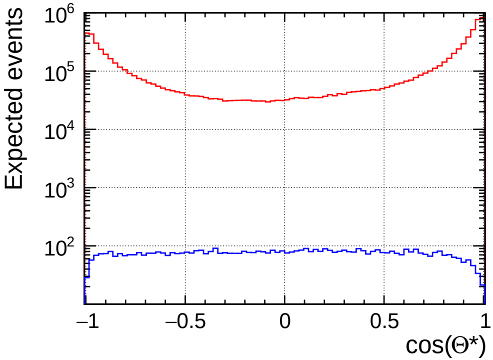


Signal of 50 GeV scalar production normalized to 1% of SM cross section

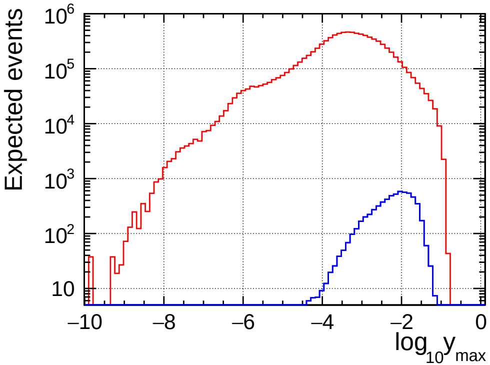
BDT input variables

Signal and **SM background** event distributions, all Z decays.

Scalar decay angle (in CMS):

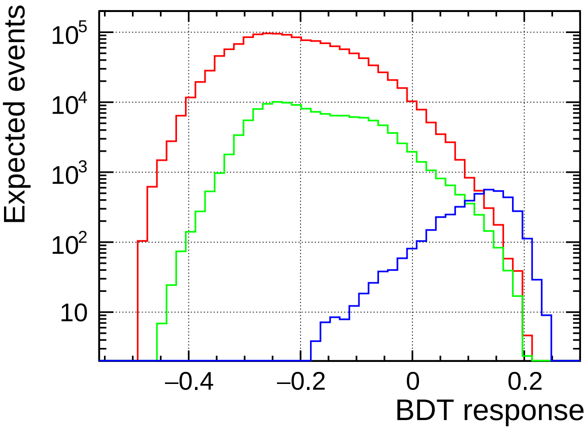


Clustering parameter:



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

BDT response distribution

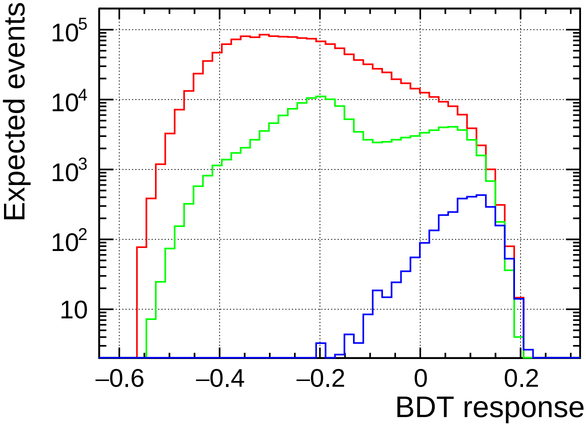


Example of BST response distribution

- total SM background
  - semi-leptonic ZZ contribution
- signal of 50 GeV scalar production

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

BDT response distribution

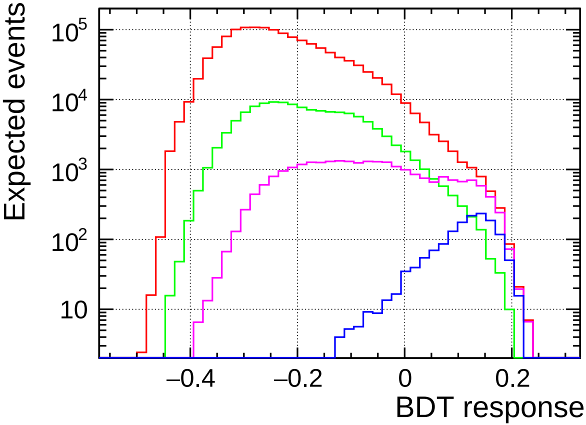


Example of BST response distribution

- total SM background
  - semi-leptonic ZZ contribution
- signal of 95 GeV scalar production

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

BDT response distribution



Example of BST response distribution

- total SM background
  - semi-leptonic ZZ contribution
  - SM Higgs production
- signal of 125 GeV scalar production

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

BDT response cut

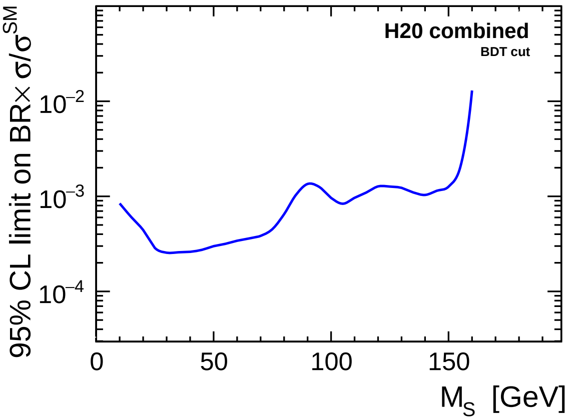
Default approach in TMVA is to select BDT cut optimal for signal significance.

Expected uncertainty on the signal cross section, assuming no signal is observed, can be then calculated as:

$$\delta_\sigma = \frac{\sqrt{B}}{S} \cdot \sigma_{ref}$$

where $\sigma_{ref} = 0.01 \cdot \sigma^{SM}$. 95% CL limit on the signal cross section can be then calculated as

$$\sigma_{95\%CL} = 2^{\star} \cdot \delta_\sigma = \frac{2\sqrt{B}}{S} \cdot \sigma_{ref}$$



⋆ 1.96 according to Unified Approach: G.J.Feldman, R.D.Cousins, Phys.Rev.D57:3873-3889,1998, arXiv:physics/9711021

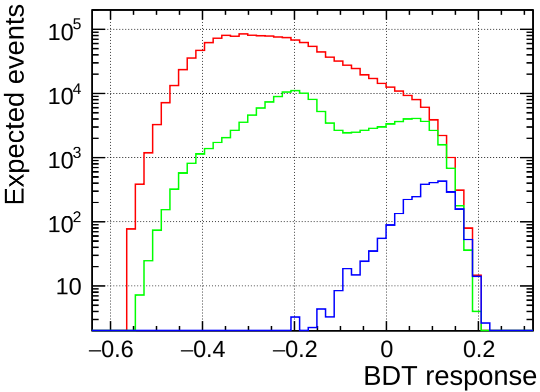
BDT histogram

BDT cut rejects 40-60% of signal events. Information on the response distribution is not used.

Better limits can be obtained 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



$M_S = 95$ GeV

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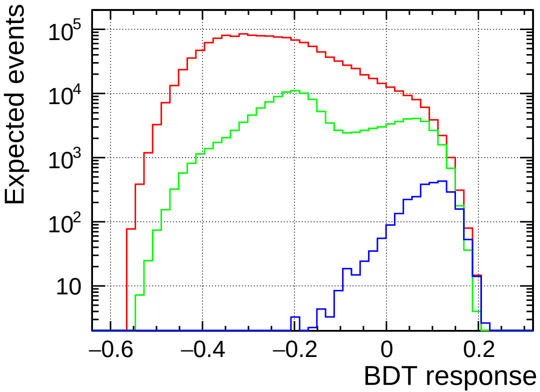
Bins with few background events combined to obtain

$$b_i = \sum w_i \geq N_{min} \quad \text{and} \quad \frac{\left(\sum w_i\right)^2}{\sum w_i^2} \geq N_{min}$$

expected events — effective MC events

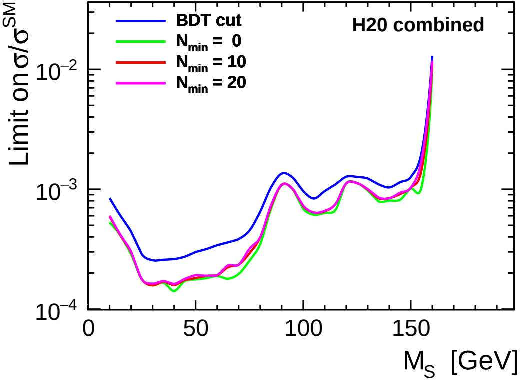
where w_i is the MC event weight.



$M_S = 95$ GeV

BDT histogram

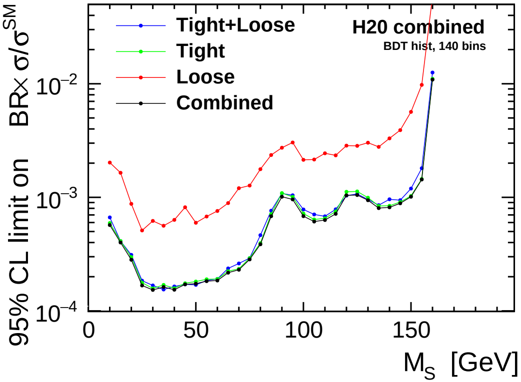
Compared to BDT cut method, limits improve by 20–40%:



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

Event selection

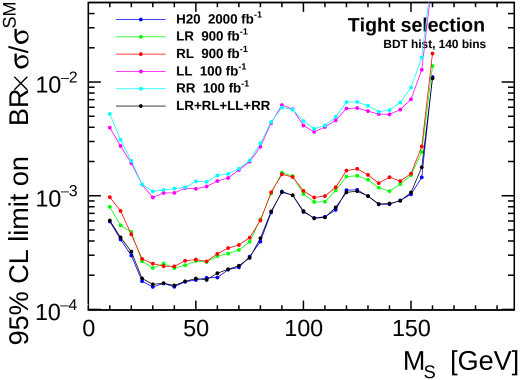
Results presented so far were obtained for "tight" selection: both tau leptons tagged



No improvement from including "loose" selection events (with only one tau lepton tagged)!

Event selection

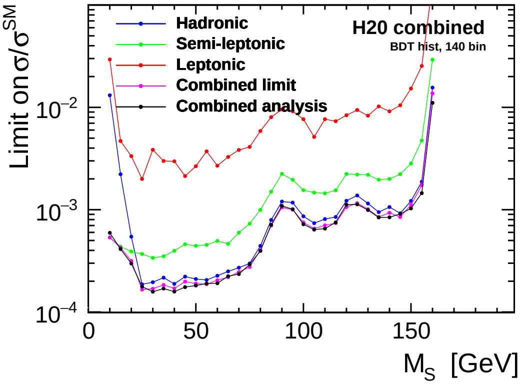
Results presented so far were obtained from combined H20 data analysis.



No improvement from combining limits calculated separately for each polarization!

Event selection

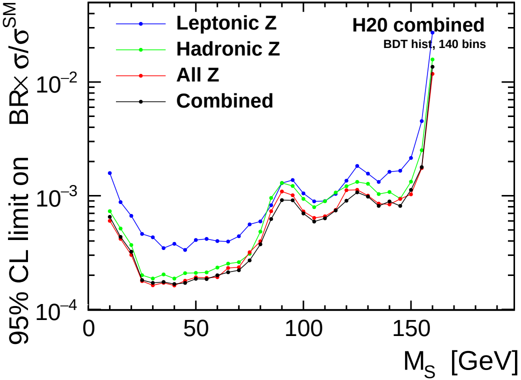
Results presented so far were obtained from all tau decay channels combined.



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

Event selection

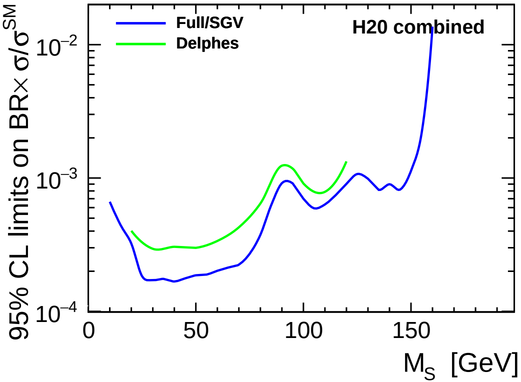
Results presented so far were obtained from all Z decay channels combined.



Small improvement from combining limits calculated separately for hadronic and leptonic Z

Final result

Tight selection, combined H20 data, combined tau decays, leptonic and hadronic Z decay limits combined:



Significant improvement compared to the previous results based on Delphes

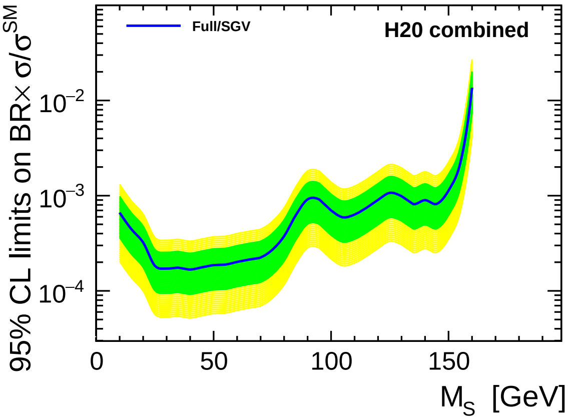
Final result

Expected limits calculated assuming no signal is observed. But we still expect statistical fluctuations in the observed background.

The actual limit resulting from the collected data can fluctuate a lot as well ⇒

Unified intervals for the constrained Gaussian distribution
G.J.Feldman, R.D.Cousins, Phys.Rev.D57:3873-3889,1998
arXiv:physics/9711021

$1\,\sigma$ and $2\,\sigma$ limit bands:



Conclusions

Full simulation/SGV analysis of exotic light scalar searches in $S \to \tau\tau$ channel completed.

Significant improvement in expected limits compared to Delphes level study.
Most likely due to better, more realistic, performance of tau jet tagging.

Results intended for presentation at late summer conferences (Corfu'2026, HDays'2026)

Future plans

Taking systematic uncertainties from background normalization into account.

Extending the study to 550 GeV