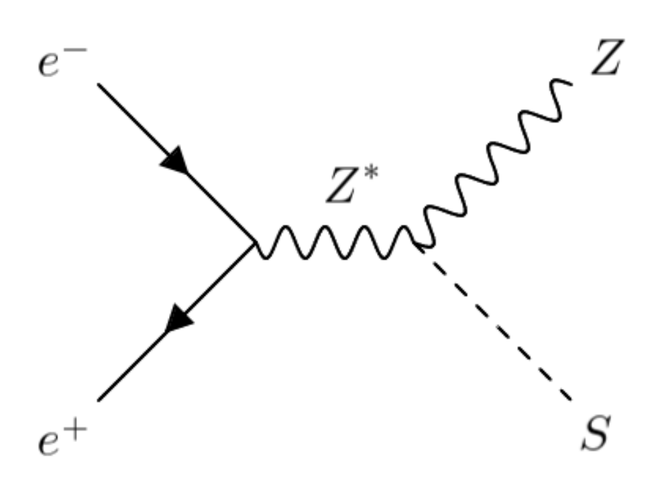
15.04.2026

RECONSTRUCTION OF EXOTIC SCALAR DECAYS INTO TAU LEPTON PAIRS

Weronika Sobień
supervised by prof. Aleksander Filip Żarnecki

INTRODUCTION

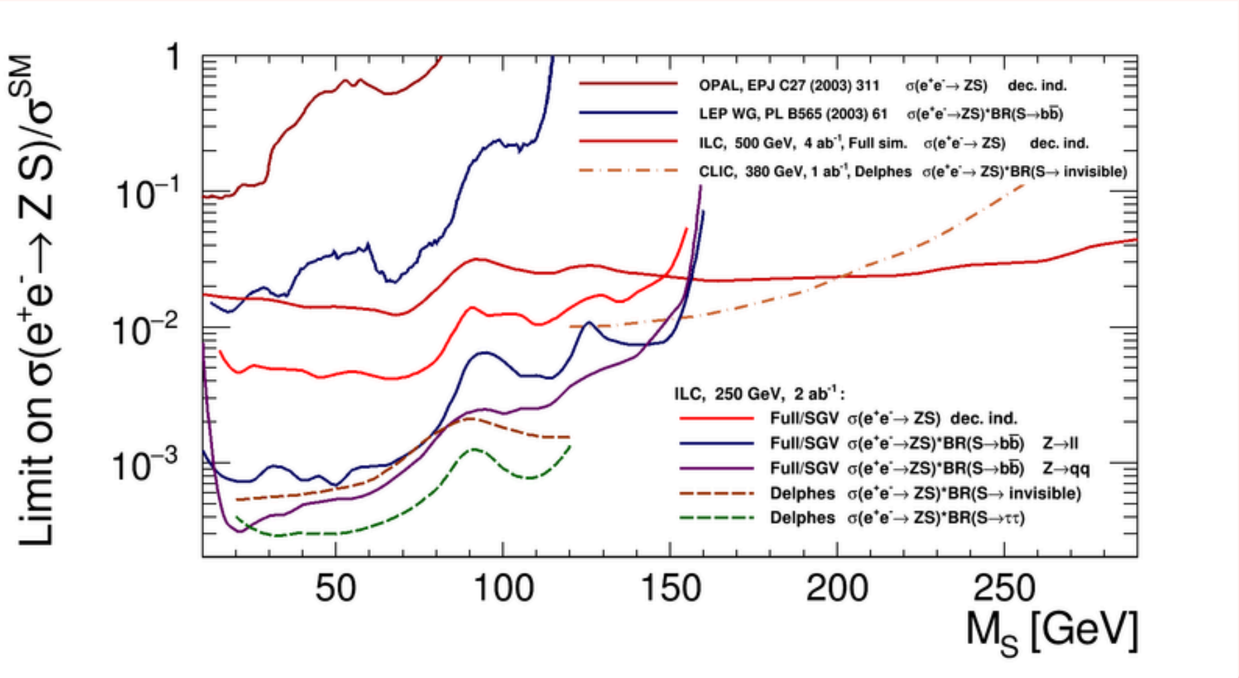


There are many models containing additional light scalar particles that are still not currently excluded by the data. Higgs factories they can be copiously produced in the scalar-strahlung process, similar to the SM Higgs boson, production.

Sensitivity to different decay channels of the exotic scalar was studied for Higgs factory running at 250 GeV.

Only decay-mode independent limits available so far at 550 GeV.

The main goal of the study is to establish sensitivity in $S \to \tau^+\tau^-$ decay channel...



SIGNAL SIMULATION

- Signal event samples for 550 GeV were generated with Whizard v3.1.5

(many thanks to Junping Tian)

Beam spectra and polarisation properly taken into account.

- Detector simulation and reconstruction was done using the SGV package.

(many thanks to Mikael Berggren)

- High-level event reconstruction in Marlin, based on ILCsoft processors

- Output stored in root format for final analysis on local computer

550 GeV

- 45 masses were generated from 20 GeV to 460 GeV with 10 GeV step, 10’000 events for each polarisation.

For each case, four production channels are considered (corresponding to different Z decay channels):

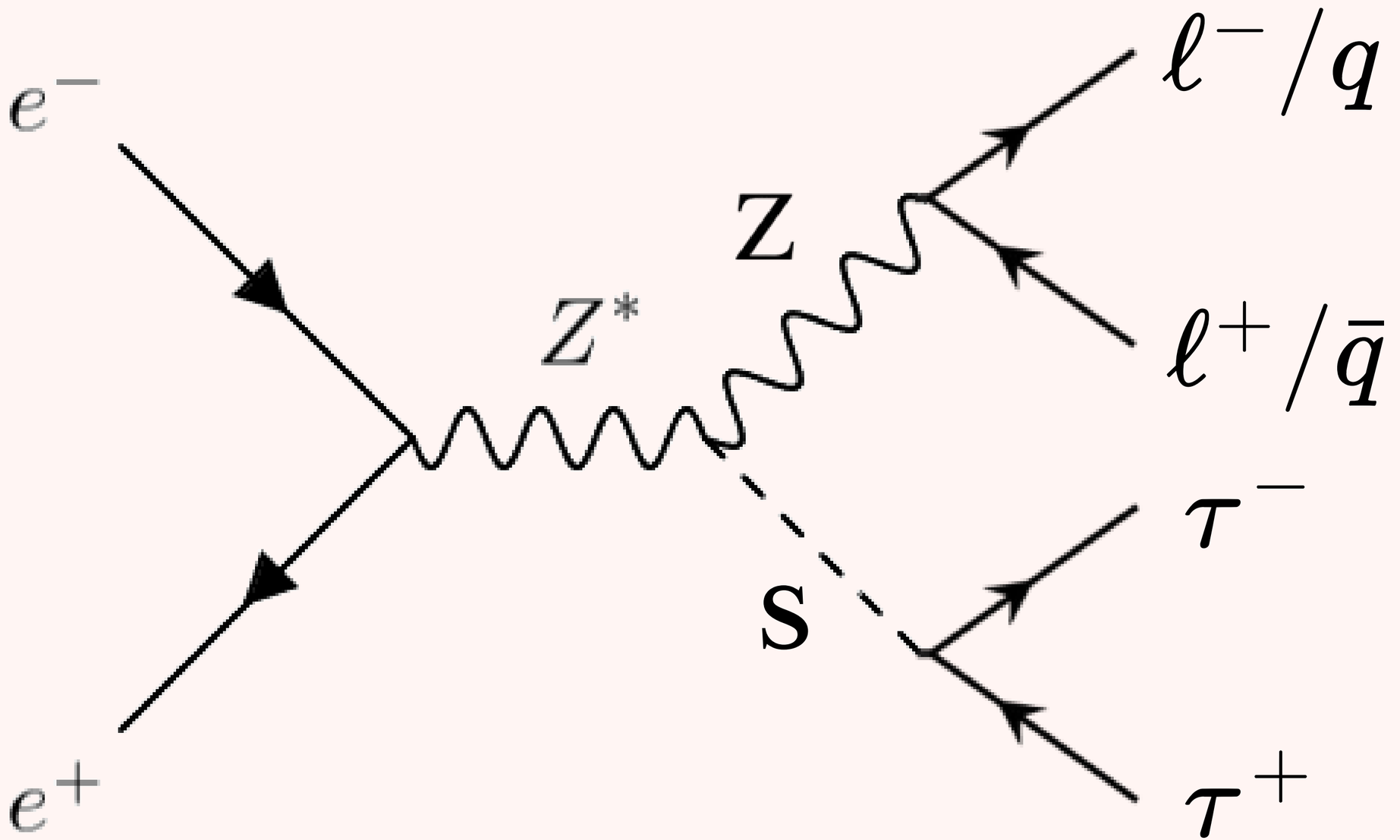
- e1e1S (including both $e^+e^- \to ZS$ with $Z \to e^+e^-$, as well as ZZ fusion channel)
- e2e2S (corresponding to $Z \to \mu^+\mu^-$)
- e3e3S ($Z \to \tau^+\tau^-$)
- qqS ($Z \to qq$)

All together, 450 files were generated with WHIZARD and processed with SGV

ILCsoft algorithms are run on ‘PandoraPFOs’ collection:

- **IsolatedPhotonTagging**
- **IsolatedLeptonTagging**
- **TaJetClustering**
- **FastJetProcessor**
  ee_kt_algorithm (Durham) algorithm run in exclusive 4 jet mode
  run on all PFOs, including leptons and tau candidates
  (only isolated photons removed)

- **EXscalarTreeWriter4jet**
  Dedicated processor to write reconstruction results to file
  For each Durham jet, PID flag is set for identified leptons and tau jets



DEVIDED INTO SMALL STEPS...

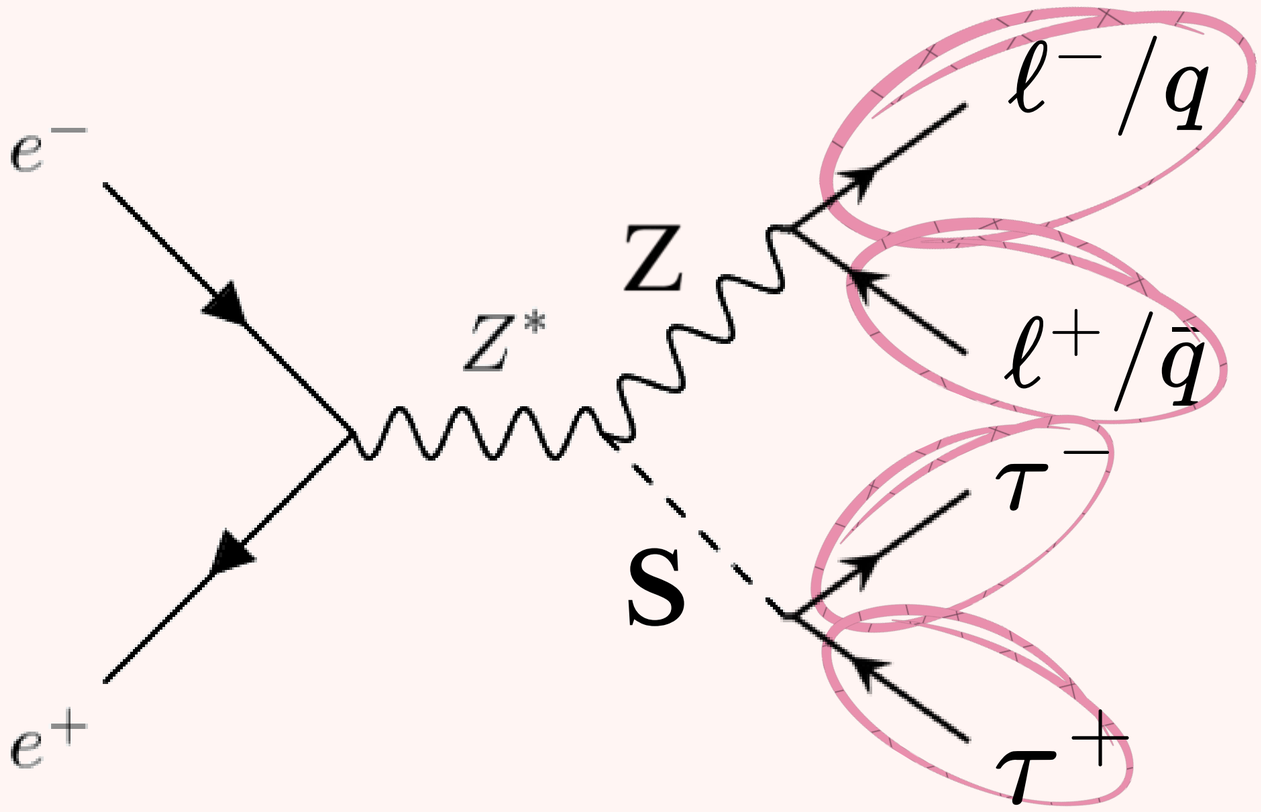
STEP 1

STEP 2

STEP 3

STEP 4

In every chanel's analysis we are always looking for four jets.



STEP 1

qqS

Reconstructs the Z and Scalar from a forced 4-jet final state.

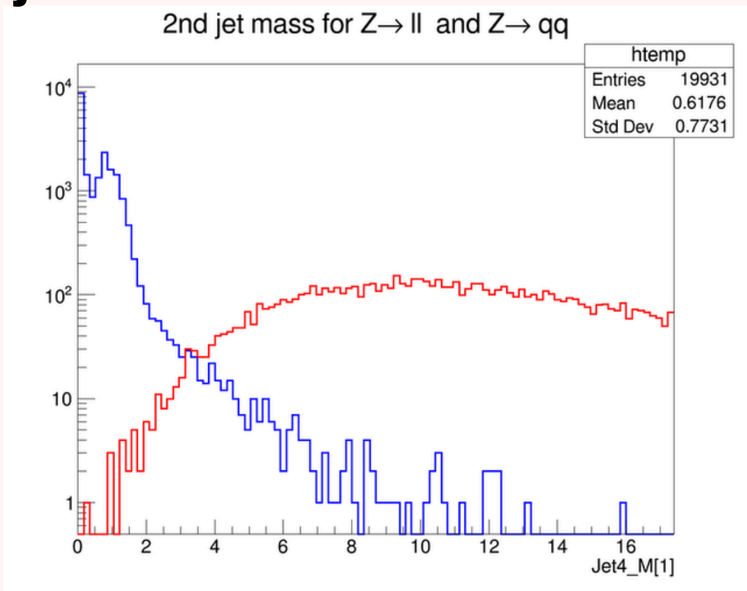
STEP 2

- **Assigns the two heaviest jets to the Z boson (~91 GeV), and the two remaining, lighter jets to the Scalar S.**
- **Enforces a strict physical mass limit: the invariant mass of the Scalar jets must be < 3.0 GeV.**

STEP 3

STEP 4

lls



STEP 1

qqS

STEP 2

- Searches for two jets containing isolated leptons that strictly conserve flavor and charge.
- If multiple lepton pairs exist, selects the pair with an invariant mass closest to the nominal Z mass.
- The two remaining jets are automatically assigned to the S.
- The invariant mass of the S candidate jets must be < 3.0 GeV to guarantee they are true, narrow tau jets.

STEP 3

STEP 4

llS

$e^- e^+$
$\mu^- \mu^+$

Reconstructs the Z and Scalar from a 4-jet final state containing exactly two primary leptons (electrons or muons).

STEP 1

Categorizes the S decay into its three physical sub-channels: Hadronic-Hadronic (Had-Had), Lepton-Hadronic (Lep-Had), or Lepton-Lepton (Lep-Lep).

STEP 2

- **First, scans the Scalar candidate jets for the presence of isolated electrons or muons, which clearly indicate a leptonic tau decay.**
- **If a jet does not contain an isolated lepton $\longrightarrow$ physical deduction. Because our previous mass cut < 3.0 GeV already eliminated broad QCD background jets, any remaining narrow jet without a lepton must be a hadronic tau decay.**

STEP 3

Based on the decoded identities of the two S jets, the event is sorted into:

STEP 4

- **Had-Had: Both jets are hadronic taus.**
- **Lep-Had: One leptonic decay, one hadronic decay.**
- **Lep-Lep: Both taus decayed leptonically.**

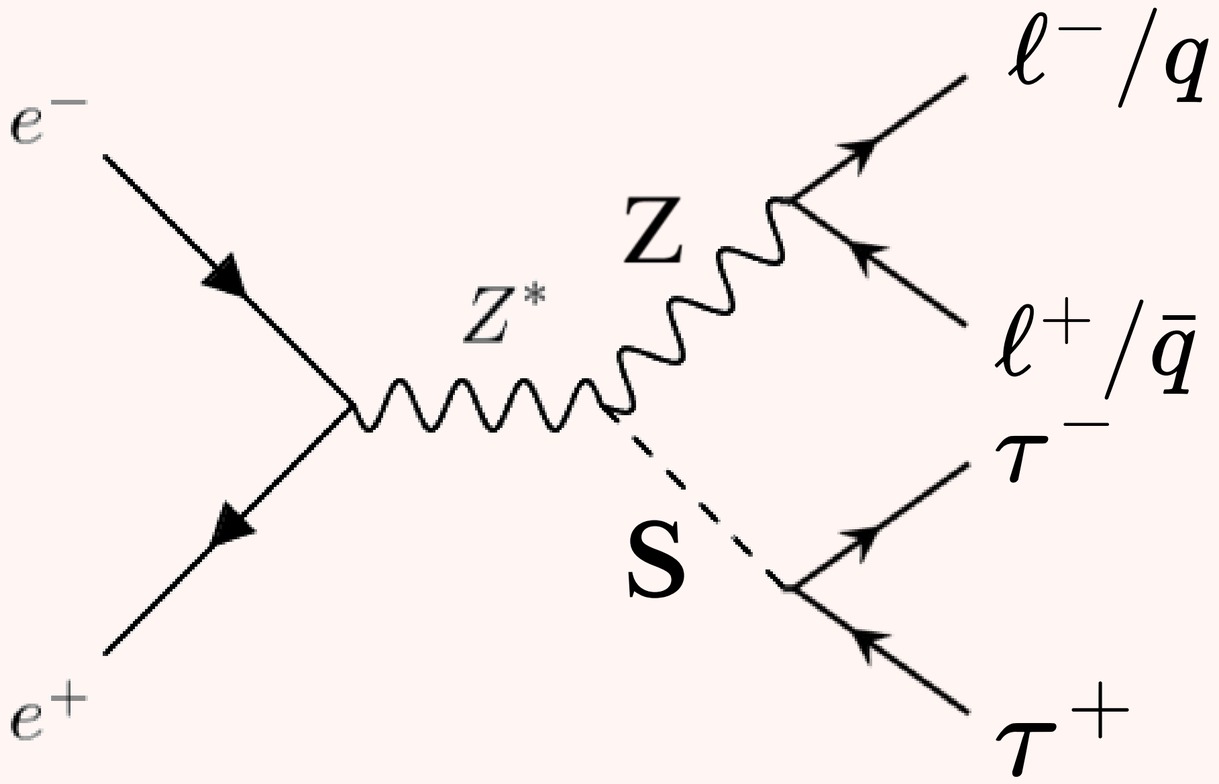
STEP 1

STEP 2

STEP 3

STEP 4

The Scalar decays into taus.



$$M_{vis} < M_S$$

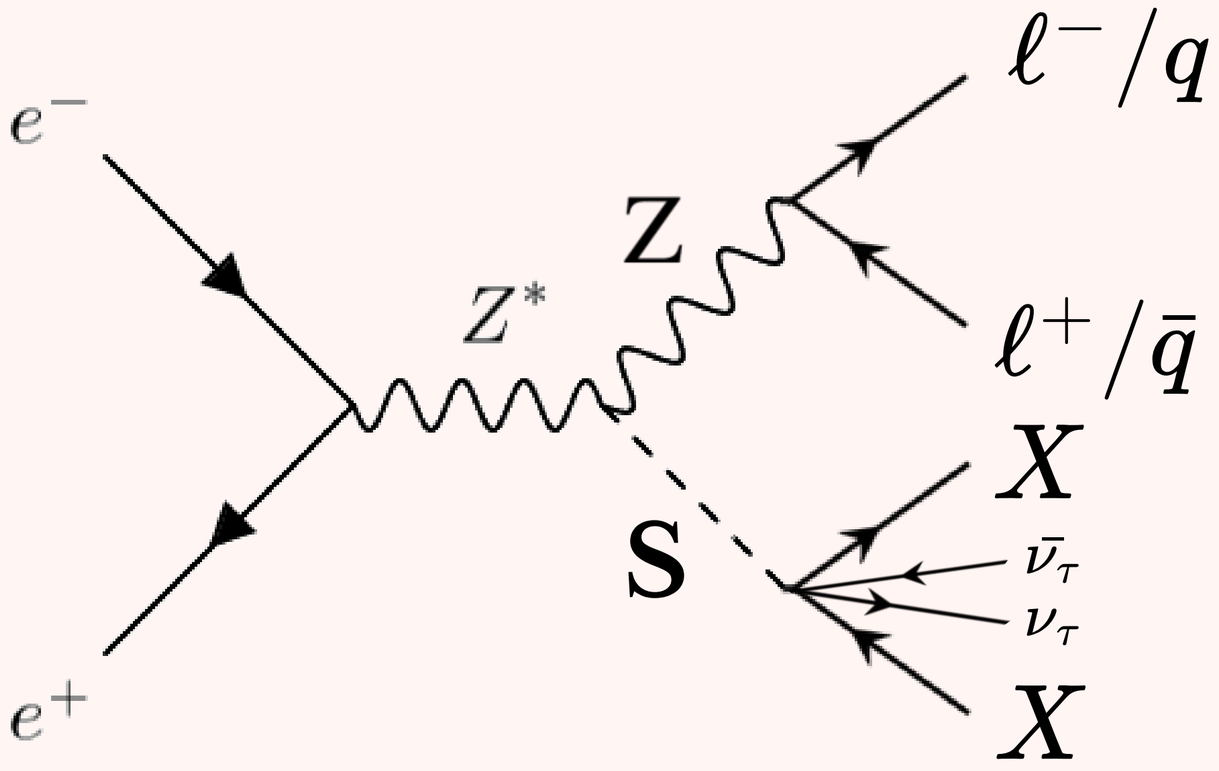
STEP 1

The Scalar decays into taus.
Every tau decay emits at least one neutrino, which escapes the detector undetected.

STEP 2

STEP 3

STEP 4



Collinear Approximation (4-Momentum)

STEP 1

Taus are highly boosted, so neutrinos are emitted in the exact same direction as the visible tau jets. The total Missing Transverse Momentum is entirely attributed to the two neutrinos.

$$\vec{p}_{miss} = E_{\nu_1}\hat{n}_1 + E_{\nu_2}\hat{n}_2$$

STEP 2

(where $\hat{n}_{1,2}$ are the direction unit vectors of the visible tau jets)

Shinichi Kawada et al. “A study of the measurement precision of the Higgs boson decaying into tau pairs at the ILC”. Eur. Phys. J. C 75.12 (2015), p. 617. doi: 10.1140/ epjc/s10052-015-3854-2. arXiv: 1509.01885 [hep-ex].

Angle Correction

STEP 3

The transverse momentum of the S must perfectly balance the accurately measured Z ($p_T^S = p_T^Z$). Scales the momenta of the visible tau jets using their measured angles (θ, ϕ) to satisfy this transverse balance.

$$P_1 = \frac{p_T^Z}{\sin(\phi_1 - \phi_2)} \frac{\sin(\phi_S - \phi_2)}{\sin\theta_1}$$

STEP 4

(where $\phi_S = \phi_Z + \pi$ is the recoil direction)

Junping Tian. “A new method for measuring the Higgs mass at the ILC”. ILD-PHYSPUB-2019-001 (2020)

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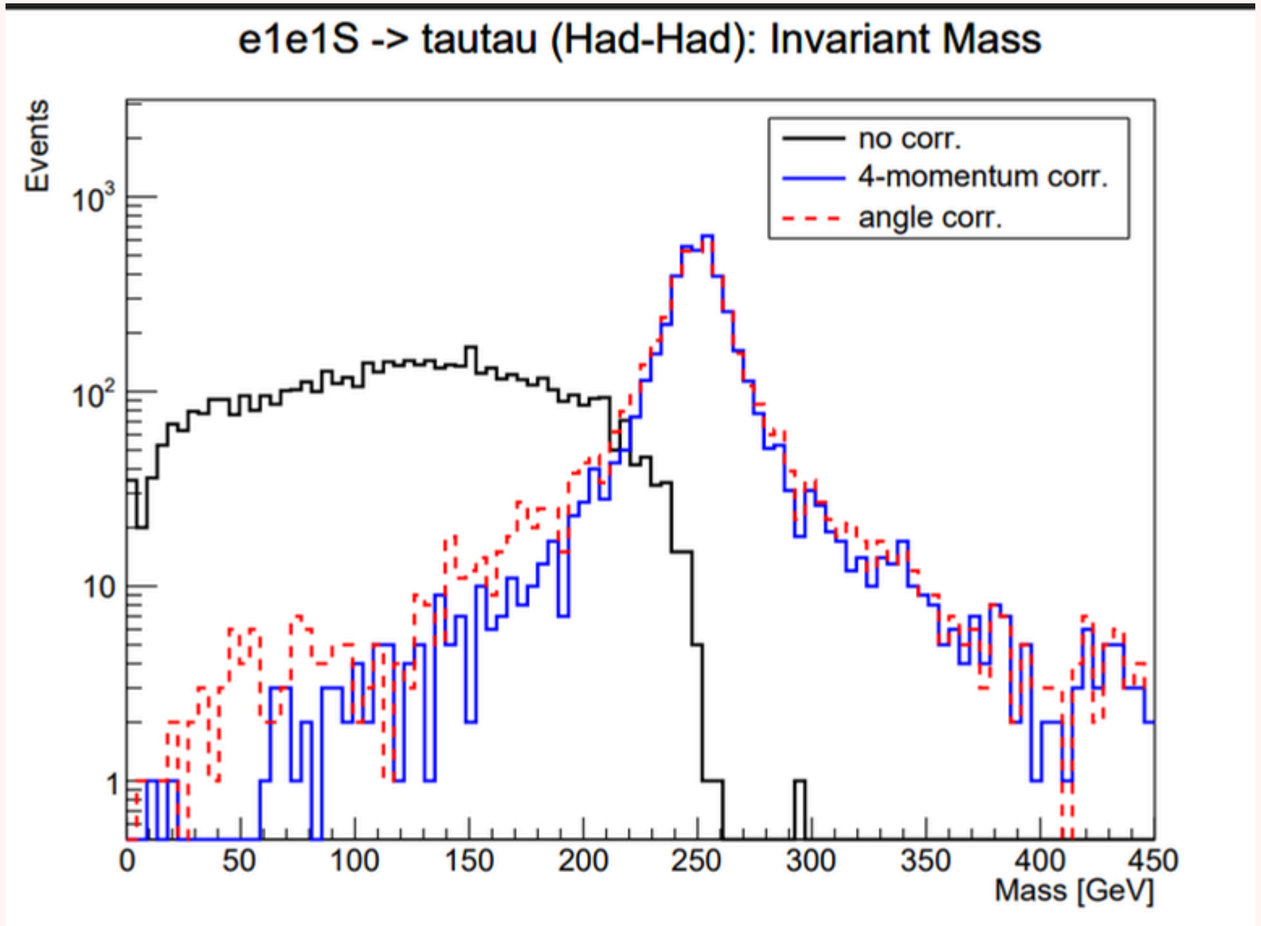
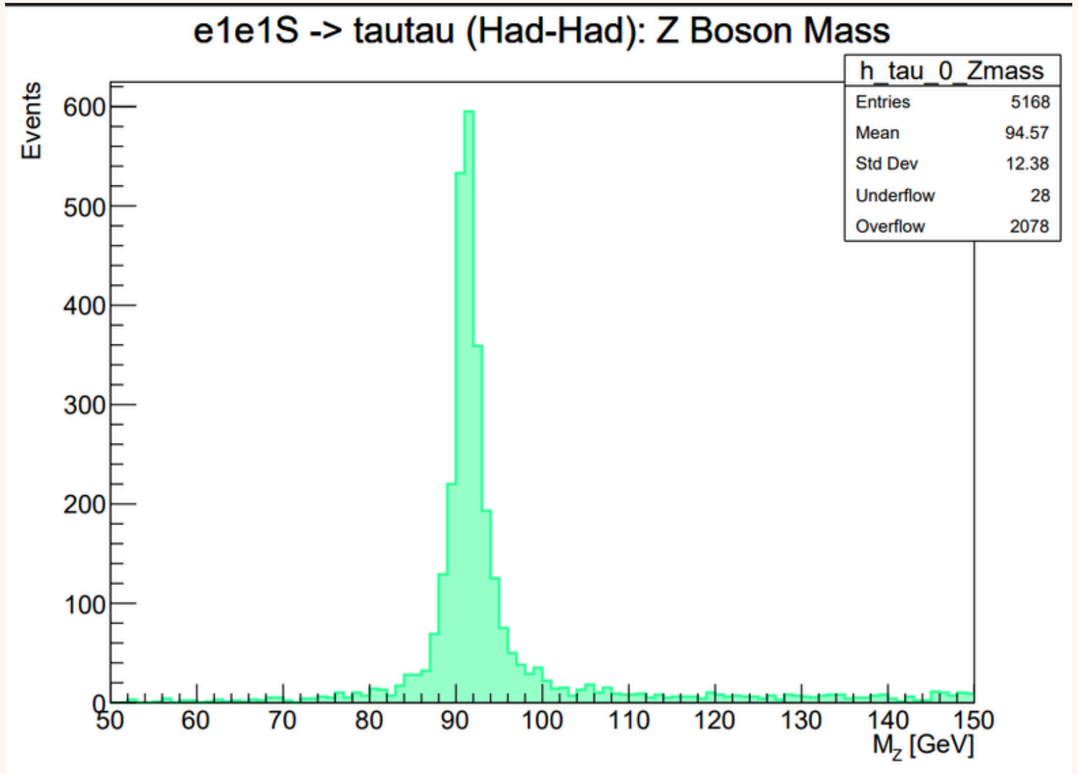
OUTCOME

$Z \to e^+e^-$

250 GeV





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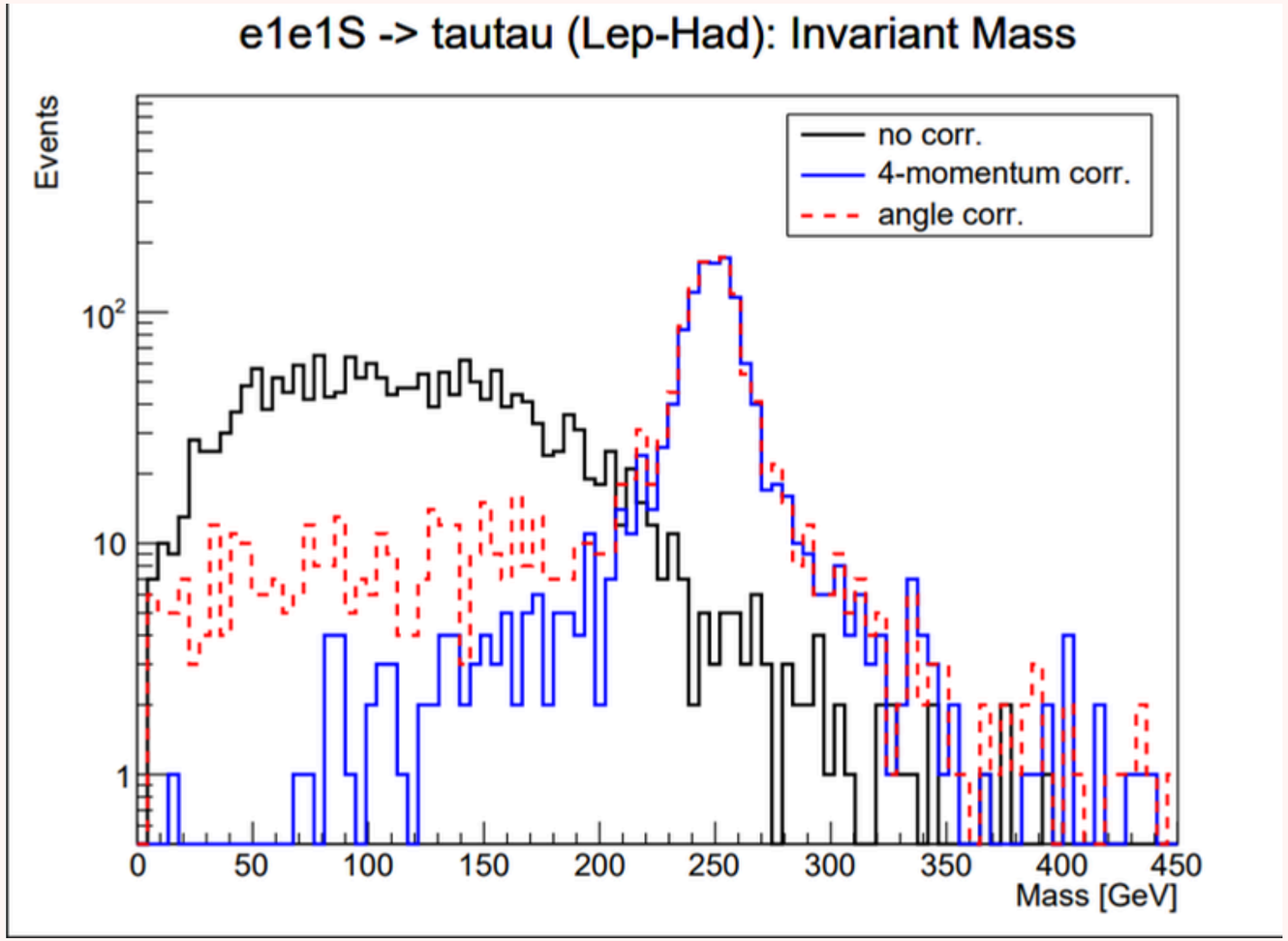
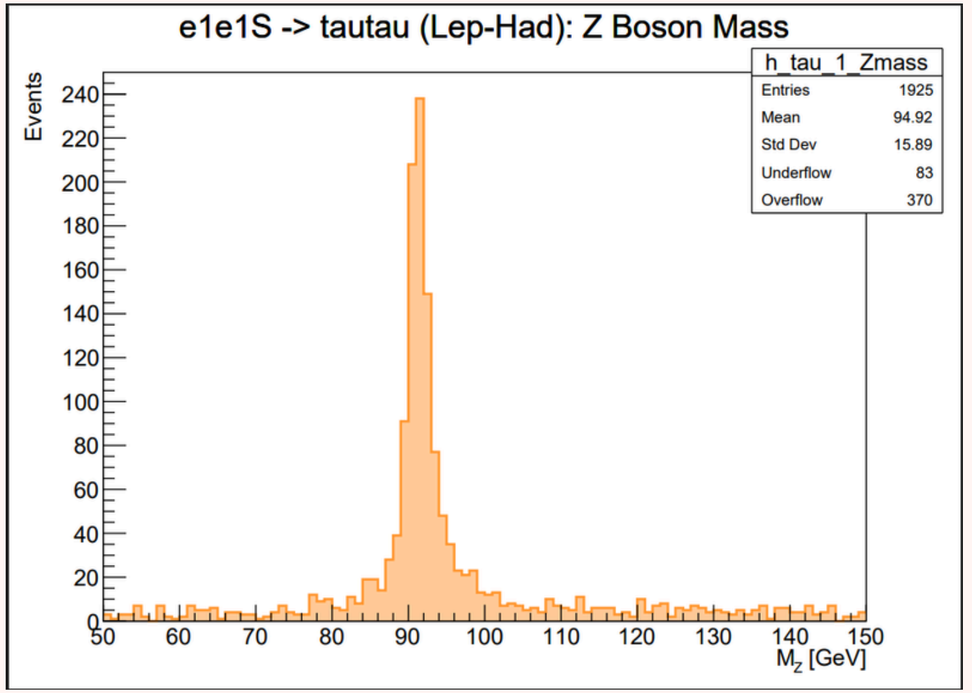
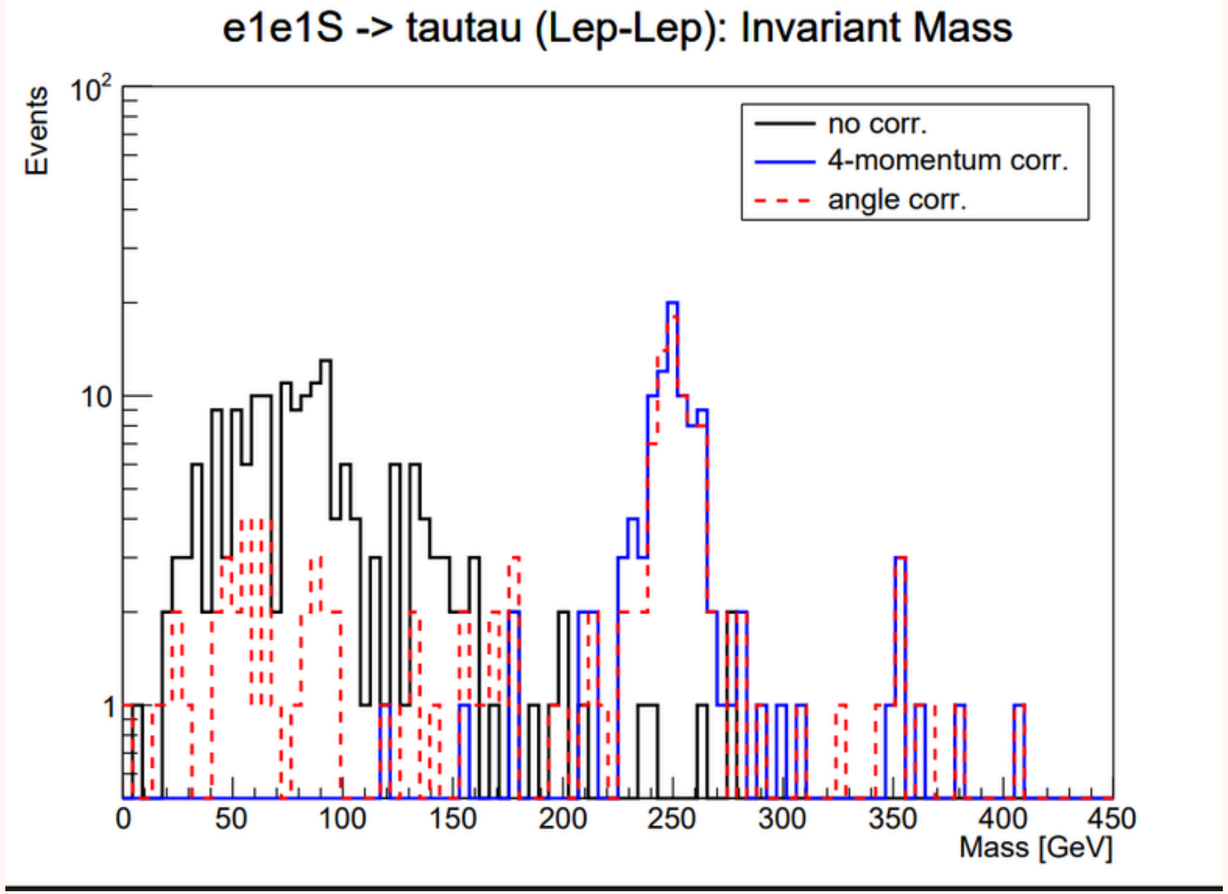


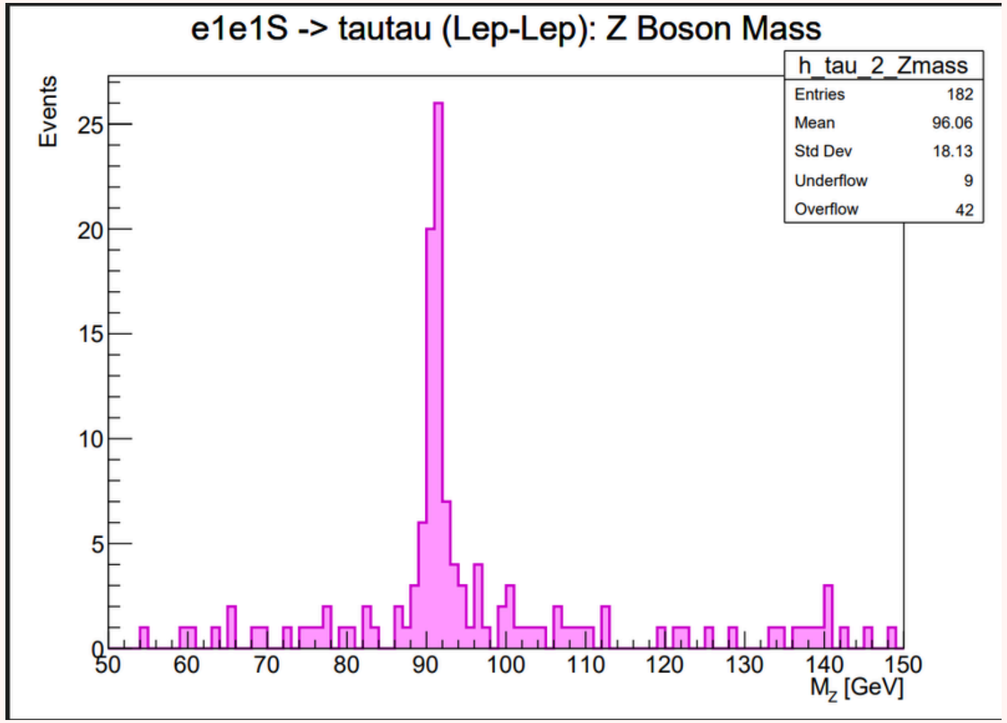


OUTCOME

$Z \to e^+e^-$

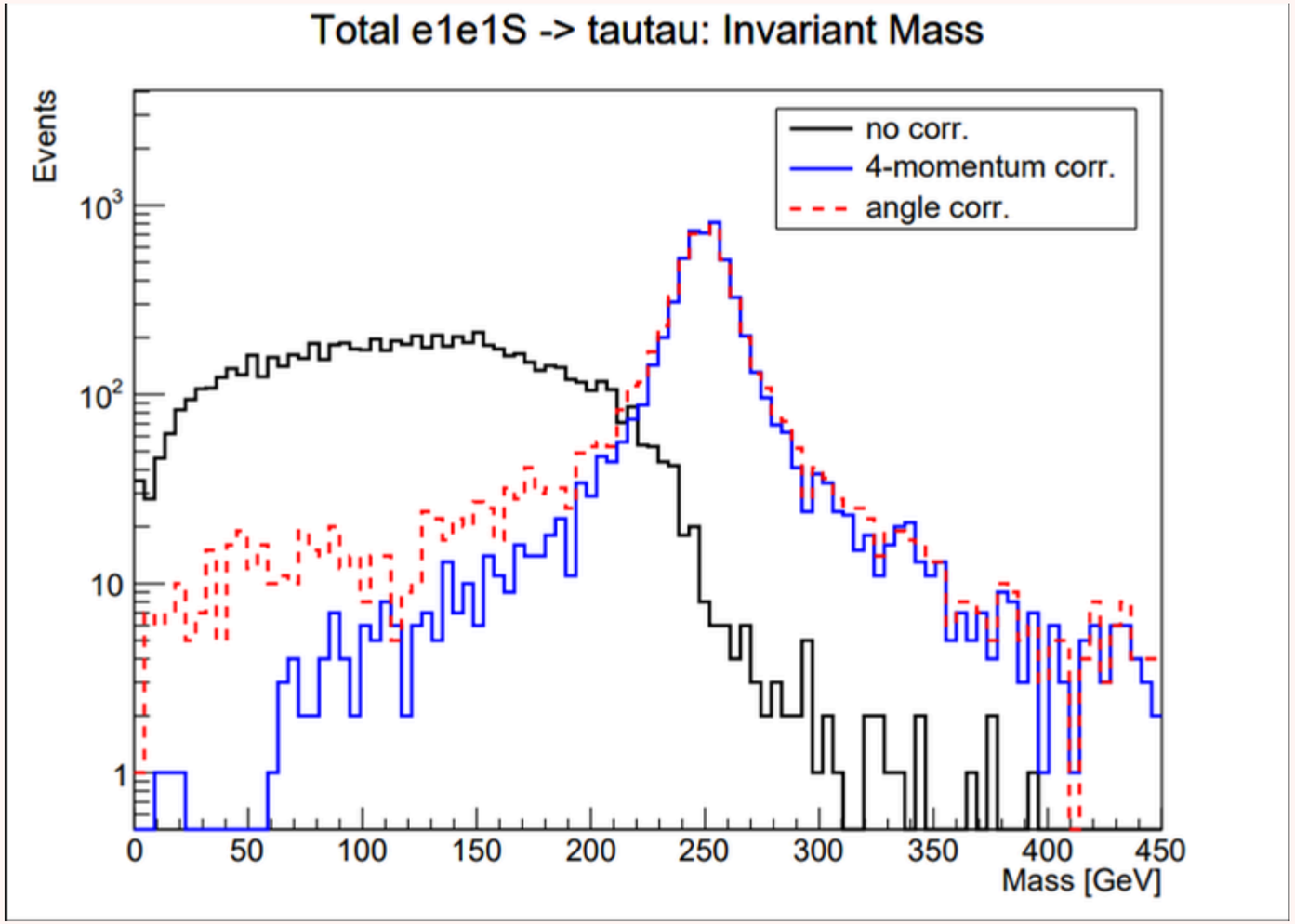
250 GeV





$Z \rightarrow e^+e^-$

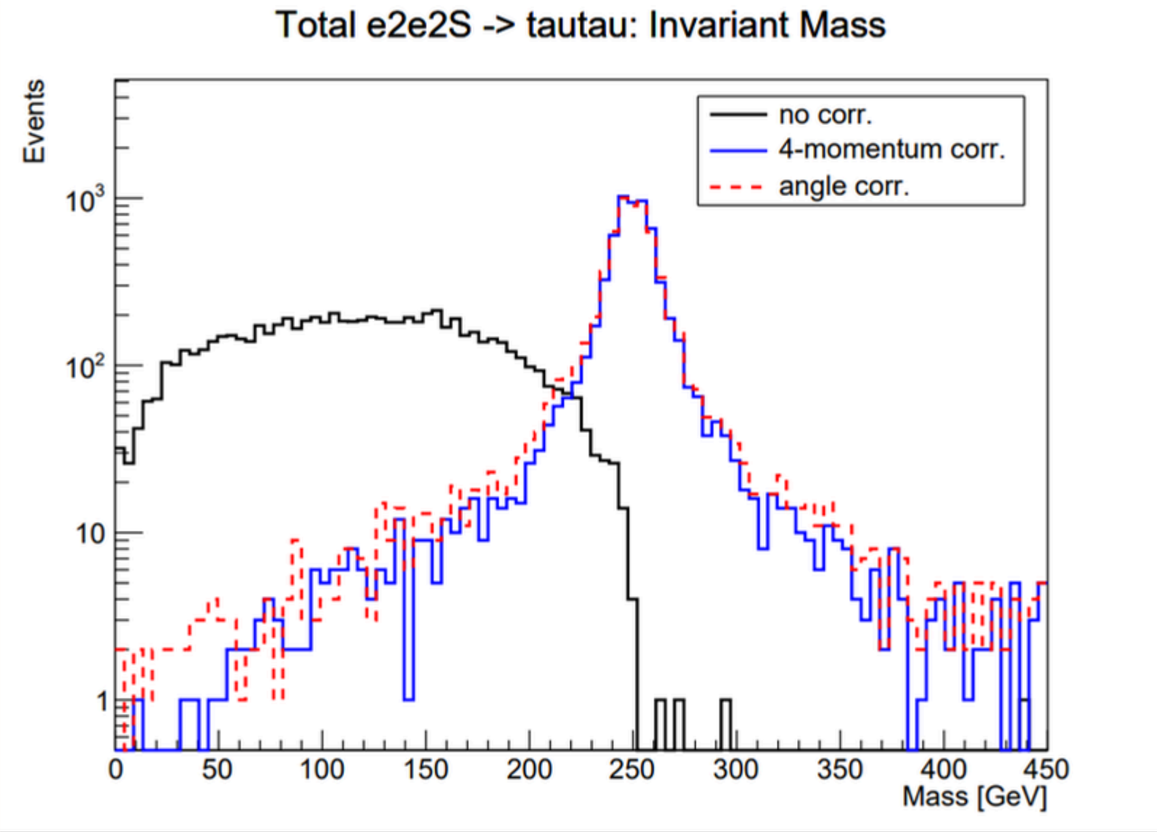
250 GeV



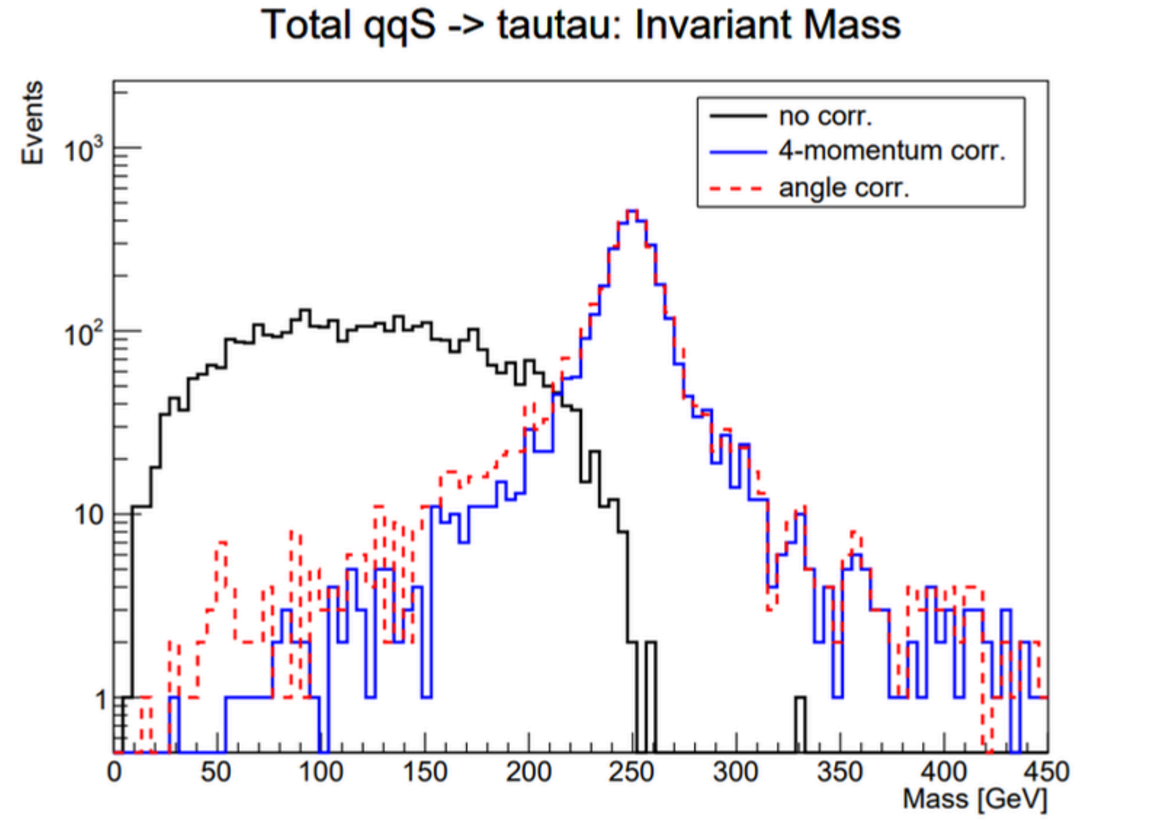
ALL TOGETHER...

250 GeV

$Z \to \mu^+\mu^-$



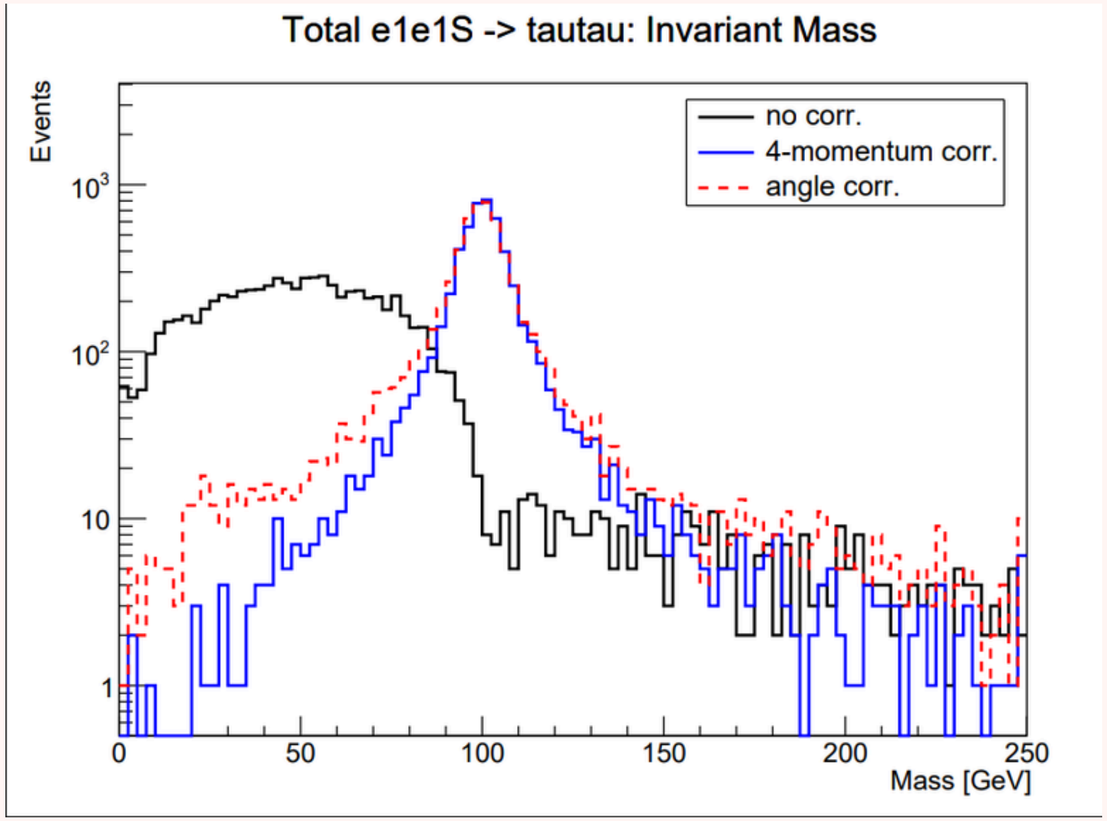
$Z \to hadrons$



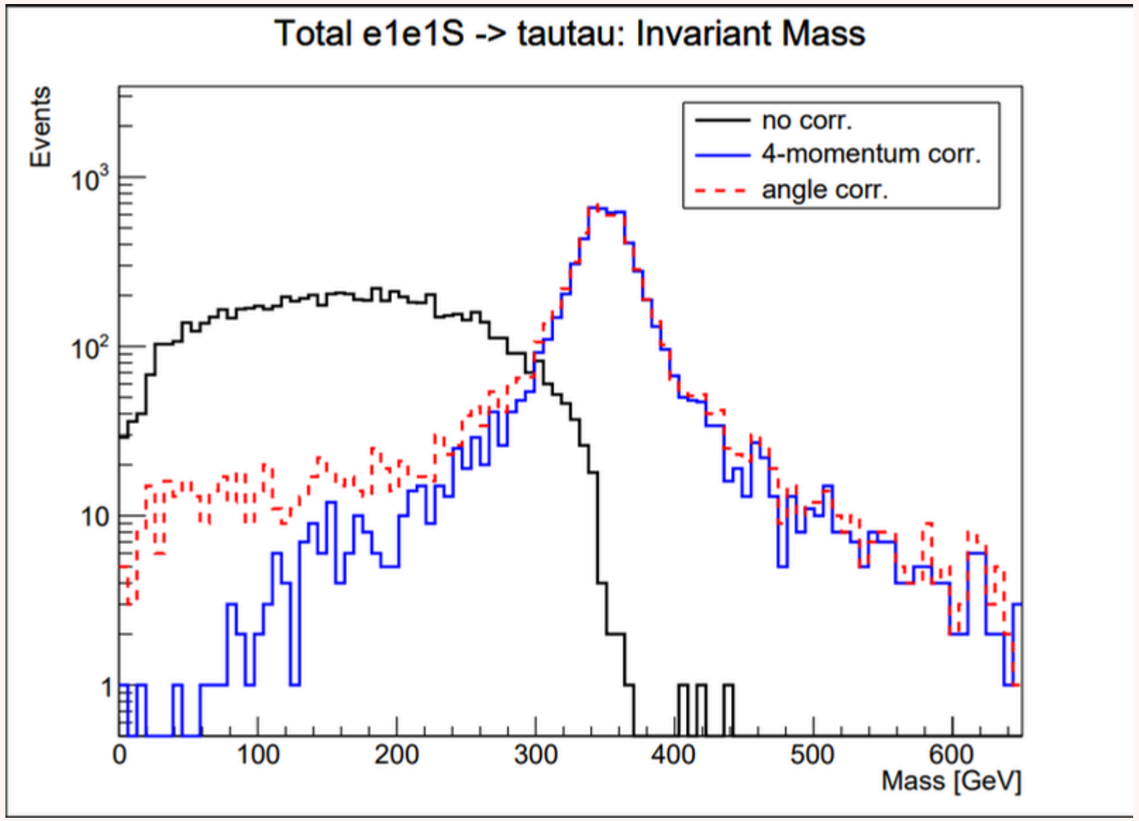
... FOR THE OTHER Z BOSON DECAYS...

OUTCOME

100 GeV



350 GeV



... AS WELL AS FOR THE OTHER MASSES...

... LEADING TO ALL THE STEPS...

combined together

IN ONE CODE

- Utilizes a "Hierarchy of Hypotheses" (a decision tree). It tests the cleanest, most distinguishable physical signatures first. If an event fails a hypothesis, it cascades down to the next one. If all signal hypotheses fail, the event is rejected.

STEP 1

hypothesis 1

Leptonic decay ($Z \to ee/\mu\mu$)

- Two isolated, opposite-sign, same-flavor leptons (electrons or muons).
- The invariant mass of the pair must be the closest to the nominal Z boson mass
- If found, then event tagged as leptonic Z

- Utilizes a "Hierarchy of Hypotheses" (a decision tree). It tests the cleanest, most distinguishable physical signatures first. If an event fails a hypothesis, it cascades down to the next one. If all signal hypotheses fail, the event is rejected.

STEP 1

Hadronic decay ($Z \rightarrow qq$)

hypothesis 2

- Triggered only if hypothesis 1 fails (no clean leptons found).
- Two heaviest jets in the event.
- At least one of these jets must be a "fat jet" (Mass < 3.0 GeV), indicating a typical quark fragmentation rather than a single tau.
- If found, then event tagged as hadronic Z.

- Utilizes a "Hierarchy of Hypotheses" (a decision tree). It tests the cleanest, most distinguishable physical signatures first. If an event fails a hypothesis, it cascades down to the next one. If all signal hypotheses fail, the event is rejected.

STEP 1

hypothesis 3

Tau decay ($Z \rightarrow \tau\tau$)

- Triggered only if hypothesis 1 & 2 fail.
- 4 narrow jets.
- Calculates the invariant mass of all possible jet pairs and selects the pair closest to the Z mass.
- If found, then event tagged as tau Z.

- Utilizes a "Hierarchy of Hypotheses" (a decision tree). It tests the cleanest, most distinguishable physical signatures first. If an event fails a hypothesis, it cascades down to the next one. If all signal hypotheses fail, the event is rejected.

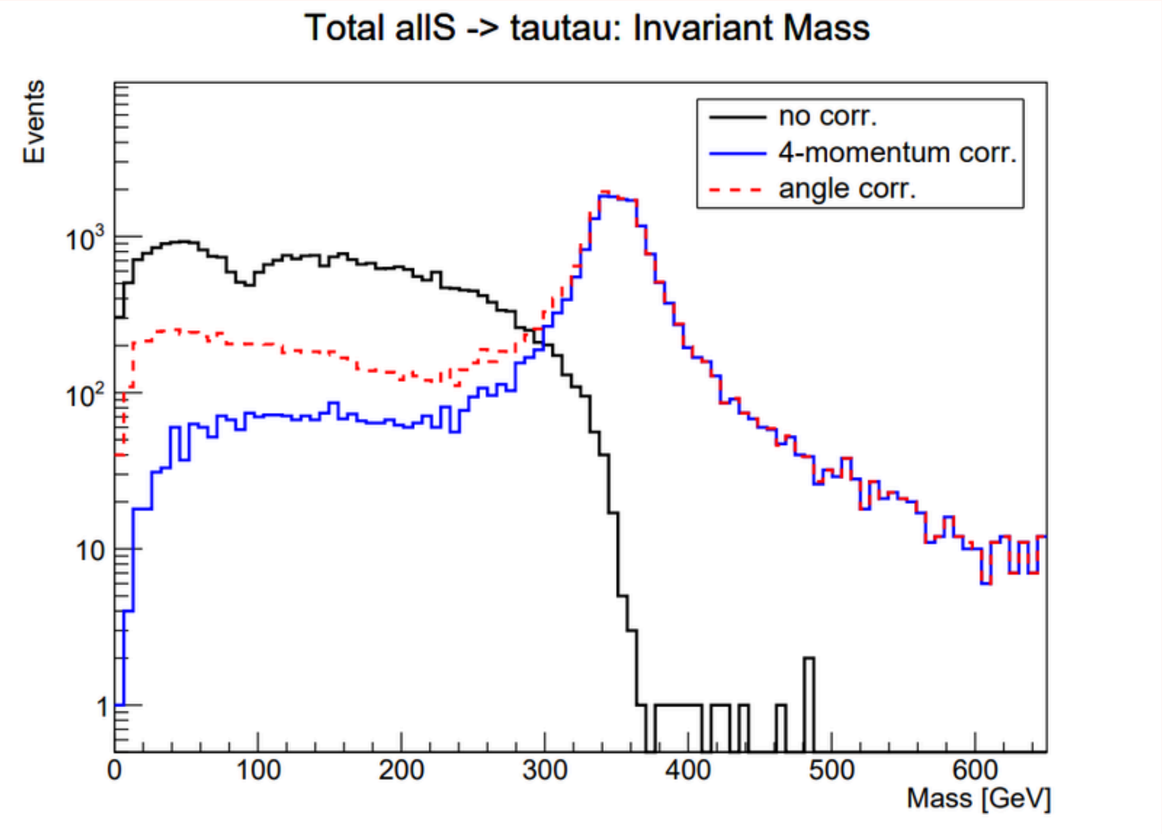
STEP 2 Exotic Scalar (S) identification

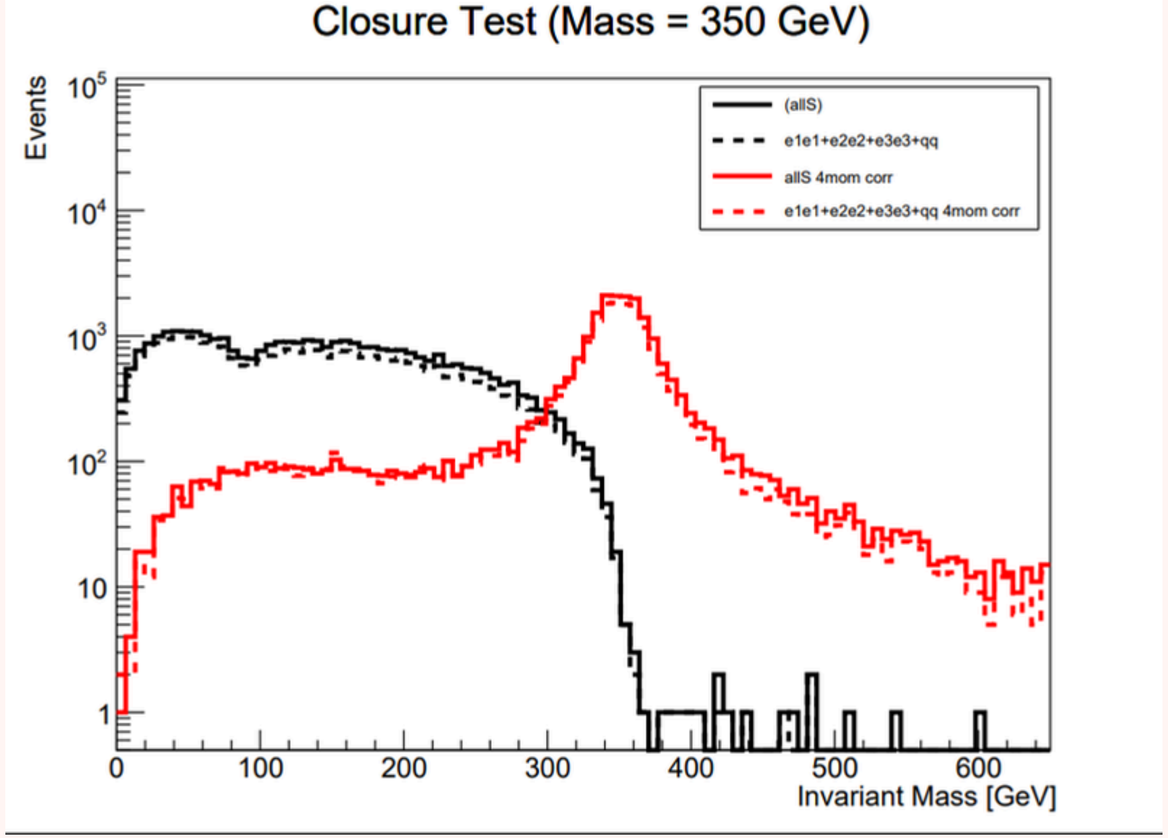
By definition, the scalar decays into a pair of taus.

Once the Z boson is successfully reconstructed, the remaining two jets in the 4-jet event are uniquely assigned to the Exotic Scalar (S).

- Using FastJet lepton-tagging flags, the scalar decay is categorized into three exclusive topological channels based on the number of identified leptons within the thin jets:
  - Had-Had: Both tau jets are fully hadronic (0 leptons).
  - Lep-Had: Semi-leptonic decay (1 lepton found).
  - Lep-Lep: Fully leptonic decay (2 leptons found).

350 GeV





All samples combined, without cross section weighting (!).

efficienty: 89%

$\sigma =$ **19.0262 GeV**

PLANS FOR THE FUTURE

We plan to continue towards the cross section limits estimate at 550 GeV:

- **apply reconstruction procedure to existing background samples**

  main background expected from WW and ZZ samples
- **adjust reconstruction procedure, if required**
- **develope signal selection MVA**

  need to be trained for each scalar mass separately
- **run MVA classification on all signal and background samples**
- **extract limits on the expected cross section times branching ratio**

250 GeV (previously done only on DELPHES level) could also be revisited

CONCLUSIONS

- **Samples generated to study exotic scalar decays to tau pairs at 550 GeV**
- **Dedicated procedure for reconstruction of scalar decays implemented**
- **Scalar mass well reconstructed after correction for missing neutrinos is applied**

Correction based on the missing transverse momentum and collinear approximation works better than the one based on the Z transverse momentum

- **Next step is to look at the background samples**

15.04.2026

THANK YOU

Weronika Sobień
supervised by prof. Aleksander Filip Żarnecki