Measurement of $\sigma(e^+e^- \rightarrow H\tau\tau) \times BR(H \rightarrow \tau\tau)$ at CLIC @ 350 GeV and 1.4 TeV

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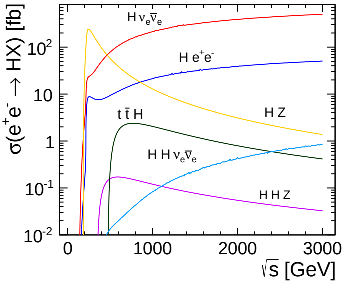
Analysis at 350 GeV and 1.4 TeV

- Signature and channels
- Reconstruction
- Cuts
- Event Selection
- Extracting statistical error on $\sigma \times \text{BR}$



Properties for both Analyses

$\sqrt{s} = 1400$ GeV

Process:	$e^+e^- \to H\nu\nu$
Particle mass:	$m_H = 120$ GeV
Final state:	$\tau\tau\nu\nu$
Branching ratio:	$H \to \tau\tau$ = 7.04%
Cross section:	248 fb $\times$ 0.07 = 17.5 fb

$\sqrt{s} = 350$ GeV

Process:	$e^+e^- \to HZ$
Particle mass:	$m_H = 126$ GeV
Final state:	$\tau\tau qq$
Branching ratio:	$H \to \tau\tau$ = 6.15%
Cross section:	93.5 fb $\times$ 0.06 = 5.75 fb

Branching ratios:

$\tau \to$ hadrons	64.8%
$\tau \to e\nu\bar{\nu}$	17.8%
$\tau \to \mu\nu\bar{\nu}$	17.4%

- Many background channels in common with study of $\tilde{\tau}_1$ pair production.
- Some with very high cross section!
- $\rightarrow$ reuse already produced data sets (although $m_{\mathrm{H}} = 120$ GeV)

Cuts on stdhep level (after generator, before simulation)

- $10 < \theta_\tau < 170$ deg, where θ_τ is the polar angle of the τ candidate
- $p_T > 20$ GeV
- $\Delta\phi < 178$ deg
- angle of τ system > 0.4 rad (23 deg)
- $40 <$ invariant mass of τ system < 650 GeV

Channels @ 1.4 TeV

Process	Cross section [fb]	Luminosity [ab^{-1}]
$ee \to H\nu\nu \to \tau\tau\nu\nu$	17.5	4.41
$ee \to \tau\tau$*	5.3	5.7
$ee \to \tau\tau\nu\nu$*	38.5	4.6
$ee \to ee\tau\tau$*	67.6	1.3
$ee \to \mu\mu\tau\tau$*	2.0	10.9
$ee \to qq\nu\nu$*	648.3	0.5
$ee \to qqee$	225.9	0.4
$\gamma\gamma \to \tau\tau$*	404.3	0.6
$\gamma\gamma \to \tau\tau\nu\nu$*	84.3	2.4
$\gamma\gamma \to ee\tau\tau$*	2.6	5.9
$\gamma\gamma \to \mu\mu\tau\tau$*	10.6	2.4
$\gamma\gamma \to qq\nu\nu$	0.63	15.0
$\gamma\gamma \to qqee$	12.2	1.6
$\gamma e \to \tau\tau e$	1795	0.5
$\gamma e \to qqe$	3283	0.3
$\gamma e \to qq\nu\nu e$	21.0	1.7

*cross sections after stdhep cuts, in common with $\tilde{\tau}_1$ pair production

Pre-Selection Cuts @ 1.4 TeV

Cuts on analysis level have to be stronger than stdhep cuts:

- no leptons in τ
- $15 < \theta_\tau < 165$ deg
- p_T of $\tau > 25$ GeV
- $\Delta\phi < 177$ deg
- angle between the two τs > 0.5
- $45 <$ invariant mass of τ system < 130 GeV
- Thrust < 0.99
- $20 <$ transverse mass of τ system < 400 GeV
- Number of tracks in τ candidate either 1 or 3

Forces a bit higher cuts on p_T than would be optimal for this analysis.

τ Reconstruction: The Algorithm

Jet like cone algorithm with some specific requirements according to τ properties:

1. Take charged particle with highest energy and test for seed
2. Loop charged particles and add the ones inside search cone to seed adjusting cone to new combined momentum
3. Associate neutral particles in same manner
4. Start from top to find next τ candidate
5. Combine all particles inside τ candidate to τ
6. Check for split τ candidates
7. Reject τ based on invariant mass, number of charged tracks and isolation criteria

τ Reconstruction @ 1.4 TeV

1. τ reconstruction:
   - The following parameter set was chosen for the reconstruction of τ leptons:
     - Minimum p_T to enter reconstruction: 1 GeV
     - Minimum p_T for τ seed: 5 GeV
     - Maximum for invariant mass of τ candidate: 2.5 GeV
     - Opening angle of search cone: 0.07 rad
     - Opening angle of isolation cone (relative to search cone): 0.3 rad
     - Maximum energy allowed in isolation cone: 5.0 GeV

   Results in

   - single τ efficiency: 70%,
   - fake rate for a quark: 7%
2. Analysis cuts:
   - 2 τs
   - hadronic decays only
   - 1 and 3 prong τs

Process	Cross section [fb]	avail. Lumi [ab^{-1}]
$ee \to HZ \quad (H \to \tau\tau, Z \to qq)$	5.7	6.6
$ee \to HZ \quad (H \to X, Z \to \tau\tau)$	4.6	2.4
$ee \to qq\tau\tau$ (m_H=12TeV)	70.0	1.2
$ee \to qq\tau\tau\nu\nu$	1.6	5.0
$ee \to qqqq$	5900	0.1
$\gamma\gamma \to qq\tau\tau$	4.5	0.55
$\gamma\gamma \to qqqq$	84.0	0.64
$\gamma e \to qq\tau\tau e$	1.1	2.7
$\gamma e \to qqqqe$	52.6	0.46

τ Reconstruction

1. τ reconstruction:
   - The following parameter set was chosen for the reconstruction of τ leptons:
     - Minimum p_T to enter reconstruction: 0 GeV
     - Minimum p_T for τ seed: 5 GeV
     - Maximum for invariant mass of τ candidate: 2.5 GeV
     - Opening angle of search cone: 0.1 rad
     - Opening angle of isolation cone (rel. to search cone): 0.3 rad
     - Maximum energy allowed in isolation cone: 2.0 GeV

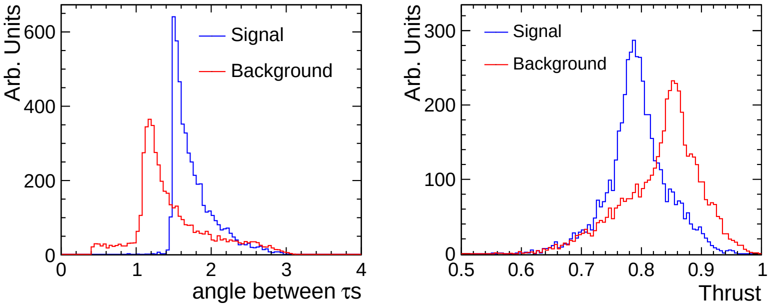
   different than 1.4 TeV reco

   Results in
   - efficiency single τ: 73%,
   - fake rate for a quark: 4.7%
2. Jet reco on rest group, forced into 2 jets
3. Analysis cuts:
   - 2 τs
   - hadronic decays only
   - 1 and 3 prong τs

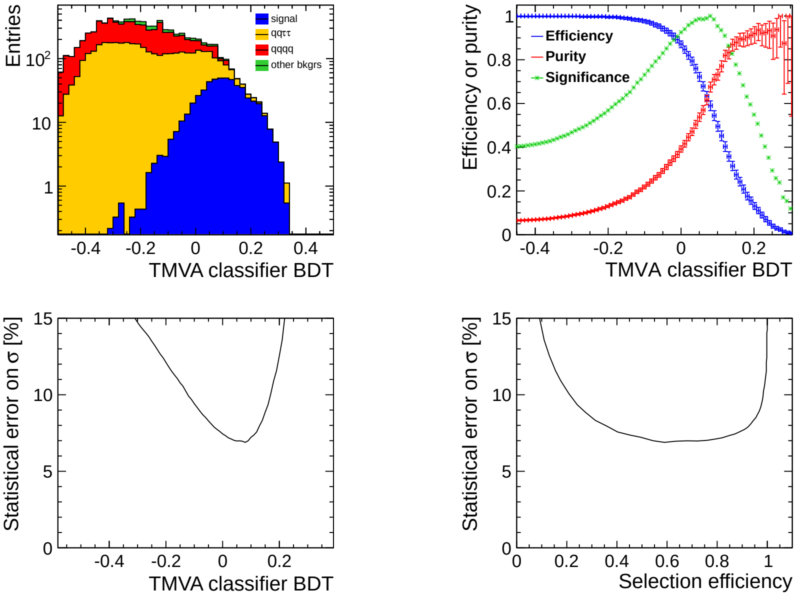
Event Selection with TMVA

Event selection with Boosted Decision Tree (BDT) based on kinematic variables of τ-system and the full event.

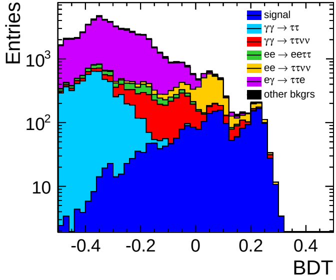
Example variables at 350 GeV:

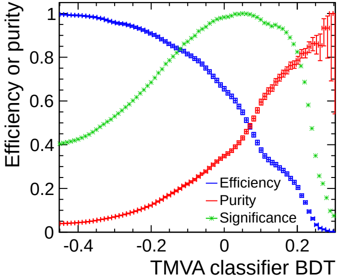


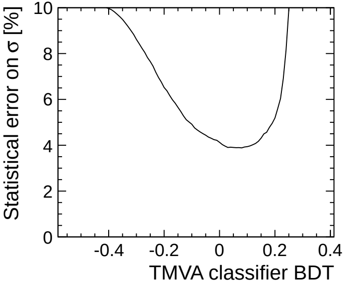
Signal Selection with BDT @ 350 GeV

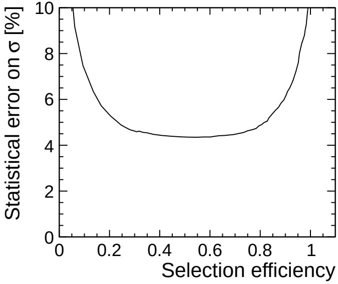


Signal Selection with BDT @ 1.4 TeV









- Method 1:

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S}$$

where S and B are summed over all bins above BDT cut.
(This what one would do for an event selection in an analysis to obtain a distribution of some variable to fit.)

- Method 2:
Make use of the full signal range!
Calculate $\frac{\Delta\sigma}{\sigma}$ for each BDT bin with signal.
Then sum up the errors:

$$x_i = \frac{\sqrt{S_i + B_i}}{S_i}$$

$$\frac{\Delta\sigma}{\sigma} = \sqrt{\frac{1}{\sum_i \frac{1}{x_i^2}}}$$

Cross Section Results

350 GeV	
Signal events (BDT>0.08)	312
Total signal events	529
Background events (BDT>0.08)	150
Signal efficiency	60%
Signal purity	67%
$\sqrt{S+B}/S$ (Method 1)	6.9%
$\sqrt{S+B}/S$ (Method 2)	6.2%

1.4 TeV	
Signal events (BDT>0.05)	1227
Total signal events	2238
Background events (BDT>0.05)	1620
Signal efficiency	55%
Signal purity	43%
$\sqrt{S+B}/S$ (Method 1)	4.3%
$\sqrt{S+B}/S$ (Method 2)	3.7%

Method 2 has a slight advantage over method 1 as this is a statical error and method 2 can use the full information contained in every bin.

Summary and Outlook

Summary

The statistical accuracy of $\sigma(e^+e^- \rightarrow H\tau\tau)\times BR(H \rightarrow \tau\tau)$ has been determined to 3.7% at 1.4 TeV and to 6.2% at 350 GeV.

Possible improvements:

- Better invariant mass reconstruction of τ-pair could improve efficiency on event selection.
- At 1.4 TeV a new production with lower stdhep cuts on transverse momentum could help.

Notes:

- 350 GeV: https://edms.cern.ch/document/1256758
- 1.4 TeV: https://edms.cern.ch/document/1231676

BACKUP

TMVA training variables at 1.4 TeV

- Missing transverse momentum $p_{\mathrm{T,miss}}$
- Thrust and oblateness of the τ system
- Sum of τ energies
- Sum of the transverse momenta of both τ candidates
- $\cos\theta_{\tau,1}$ and $\cos\theta_{\tau,2}$
- Invariant mass of the τ system
- Transverse mass of the τ system
- Angle between the two τ candidates
- θ^{miss}, where θ^{miss} is the polar angle of the missing momentum
- Accoplanarity ($\Delta\phi$) between the two τs
- Visible energy in the event
- Energy of the rest group (particles not belonging to a τ candidate)

TMVA training variables at 350 GeV

- Missing transverse momentum $p_{\mathrm{T,miss}}$
- Thrust of the full event
- Thrust and oblateness of the τ system and the quark system
- Sum of the transverse momenta of both τ candidates and quark jets
- $\cos\theta_{\tau,1}$ and $\cos\theta_{\tau,2}$
- Invariant mass of the τ system and the quark system
- Angle between the two τ candidates
- Angle between the two quark jets
- θ^{miss}, where θ^{miss} is the polar angle of the missing momentum
- $\Delta\phi$ between the two τs
- $\Delta\phi$ between the two quarks
- Visible energy in the event