# Full Simulation Study of the Higgs Branching Ratio into Tau Pairs at the 500 GeV ILC

Shin-ichi Kawada

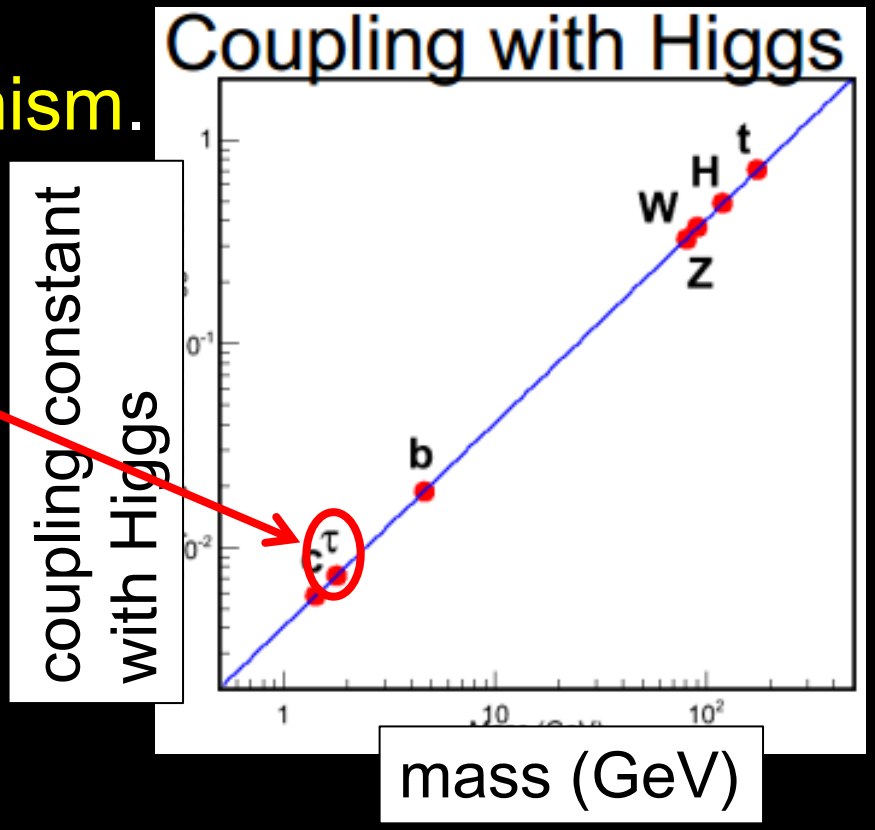
Hiroshima University

Collaborators:
Tomohiko Tanabe (ICEPP, The University of Tokyo)
Taikan Suehara (Kyusyu University)
Tohru Takahashi (Hiroshima University)
Keisuke Fujii (KEK)

# Introduction

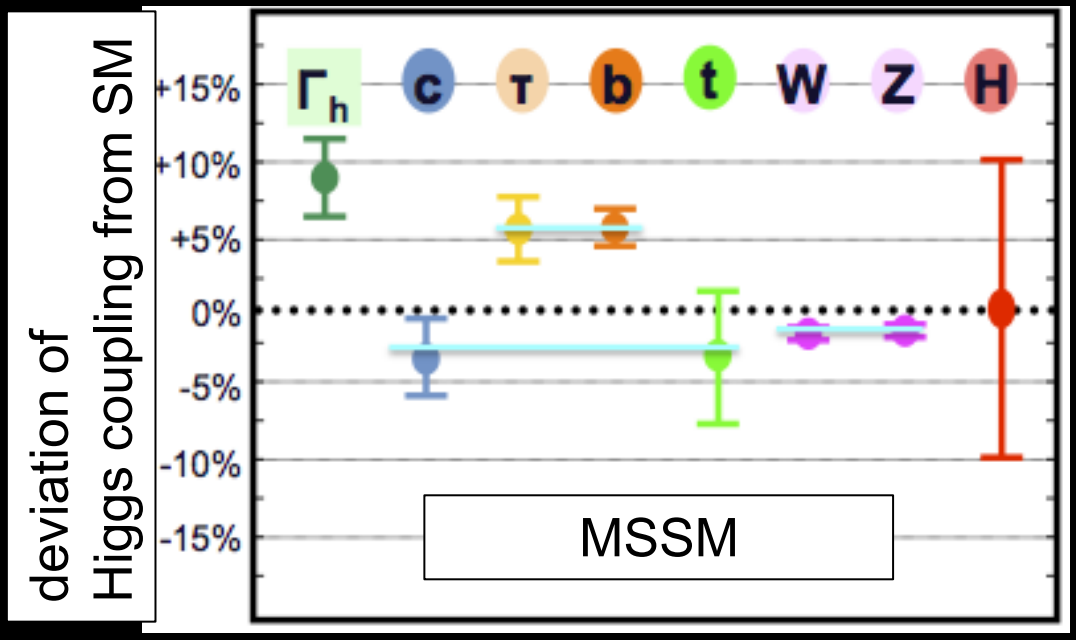
Since the discovery of Higgs boson,
the investigation of its properties has become
one of the most important themes in particle physics,
especially the verification of
the mass generation mechanism.

Full simulation of
$h \to \tau^+\tau^-$ mode



# Motivation for Precise Measurement

Any deviation in Higgs coupling and mass relation is an indication of new physics.




The small theoretical uncertainty in tau mass makes $h \to \tau^+\tau^-$ branching ratio an ideal probe for new physics.

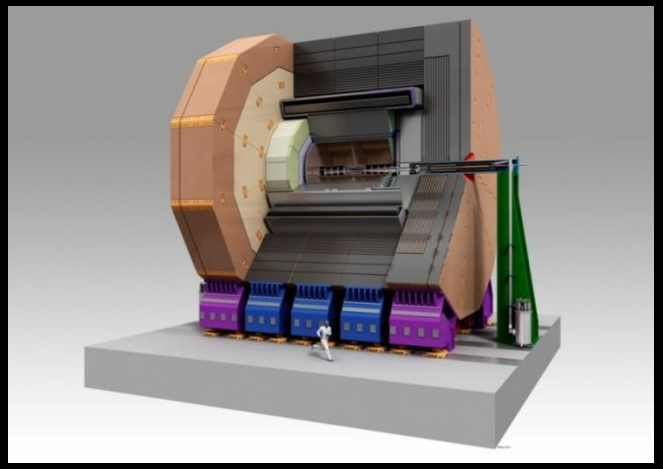
# Target of This Study

Estimation of the precision of
the branching ratio of $h \to \tau^+\tau^-$ mode

We estimated the precision with **full detector simulation (ILD)** at $\sqrt{s} = 250$ GeV and 500 GeV.

↓

talked at
ECFA 2013 @ DESY



# Simulation Settings

Higgs properties:

$M_h = 125\ \mathrm{GeV}$

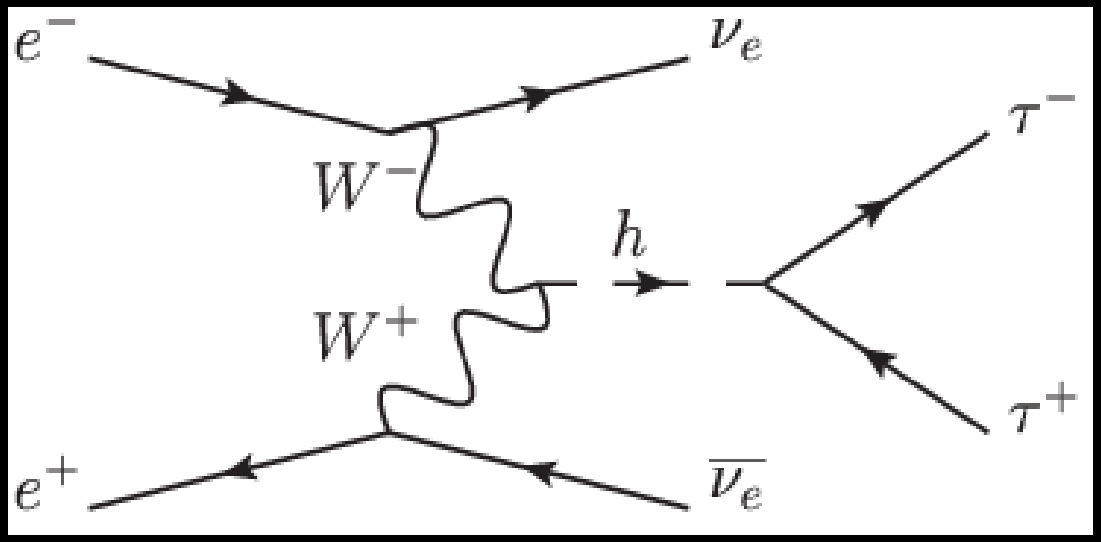
$\mathrm{Br}(h \to \tau^+\tau^-) = 6.32\ \%$ (LHC Higgs XS WG)

Machine parameters:

$\sqrt{s} = 500\ \mathrm{GeV}, \int L\, dt = 500\ \mathrm{fb}^{-1}$,

beam pol. $P(e^-, e^+) = (-0.8, +0.3)$

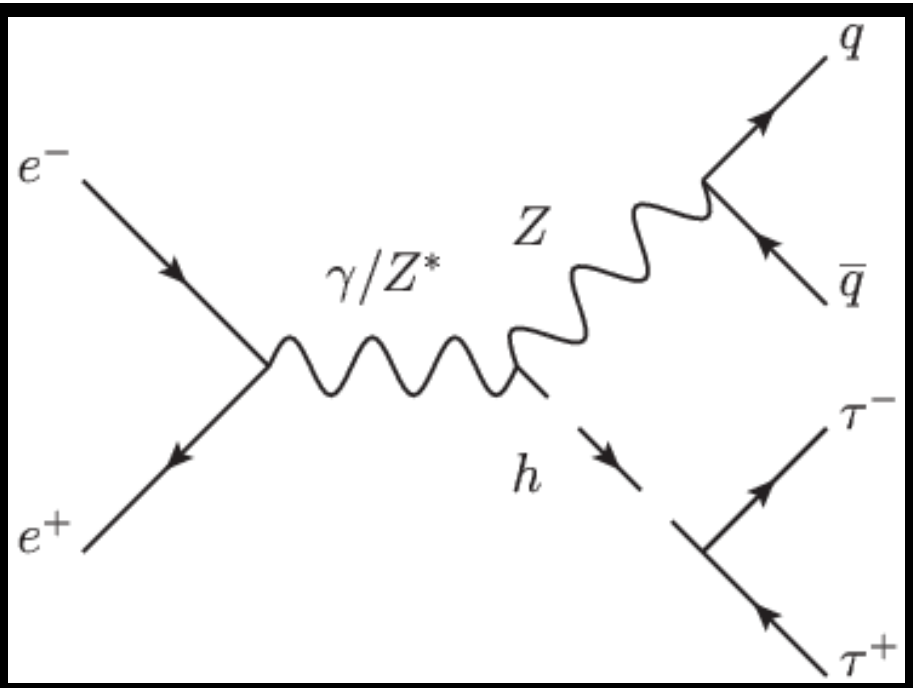
# Signals




$WW$-fusion

$e^+e^- \to \nu\bar{\nu}h$

w/ $h \to \tau^+\tau^-$




Higgs-strahlung

$e^+e^- \to Zh$

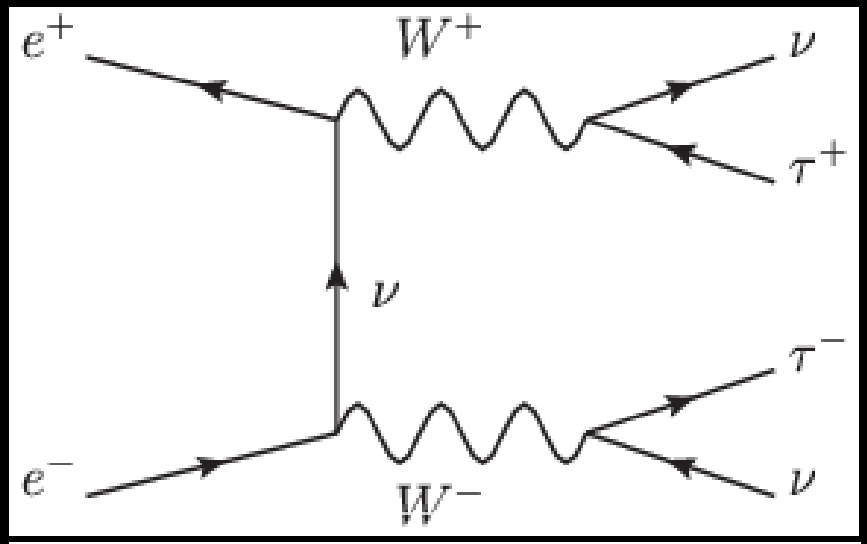
w/ $Z \to q\bar{q}, h \to \tau^+\tau^-$

# Simulation Samples

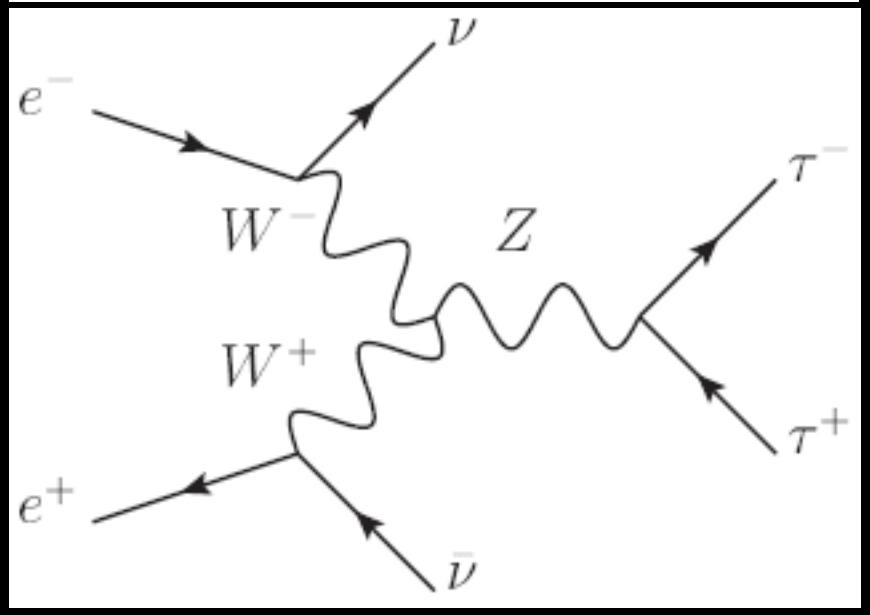
- We used 2f, 4f, 5f, 6f, $\gamma\gamma \rightarrow$ 4f, and Higgs samples.
- We included the beam-induced backgrounds ($\gamma\gamma \rightarrow$ hadrons) which induced by beam-beam interaction to the simulation samples.
- We applied the $k_t$ clustering algorithm to reject these backgrounds.

# $\nu\bar{\nu}h$ @ 500 GeV

# Main Backgrounds

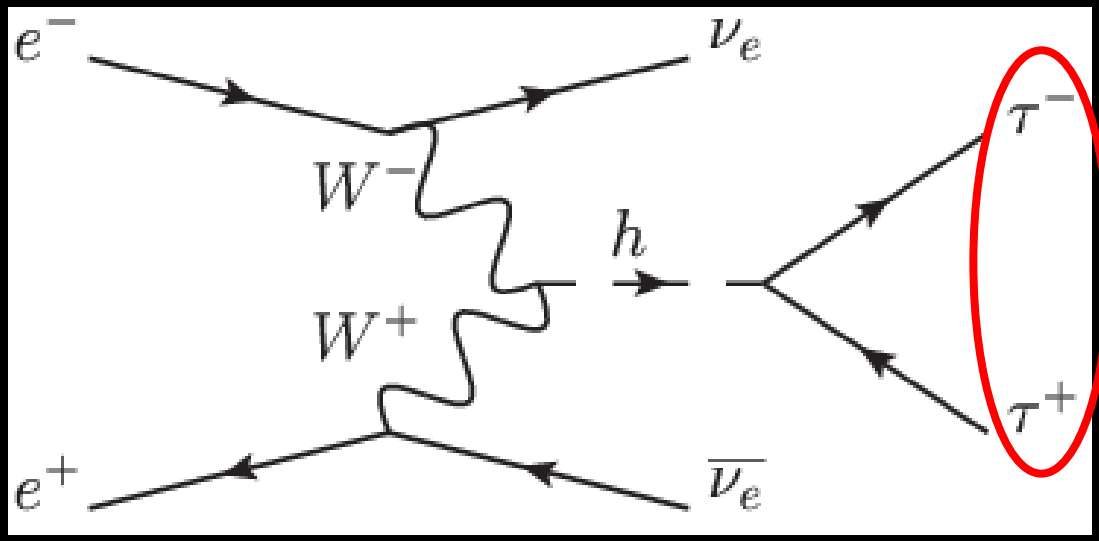



$e^+e^- \rightarrow W^+W^-(ZZ)$
$\rightarrow \nu\nu\tau^+\tau^-$
irreducible process




$e^+e^- \rightarrow \nu\bar{\nu}Z \rightarrow \nu\bar{\nu}\tau^+\tau^-$
irreducible process

# Reconstruction




(1)

(0) $k_t$ clustering

remove beam-induced backgrounds

(1) tau reco.

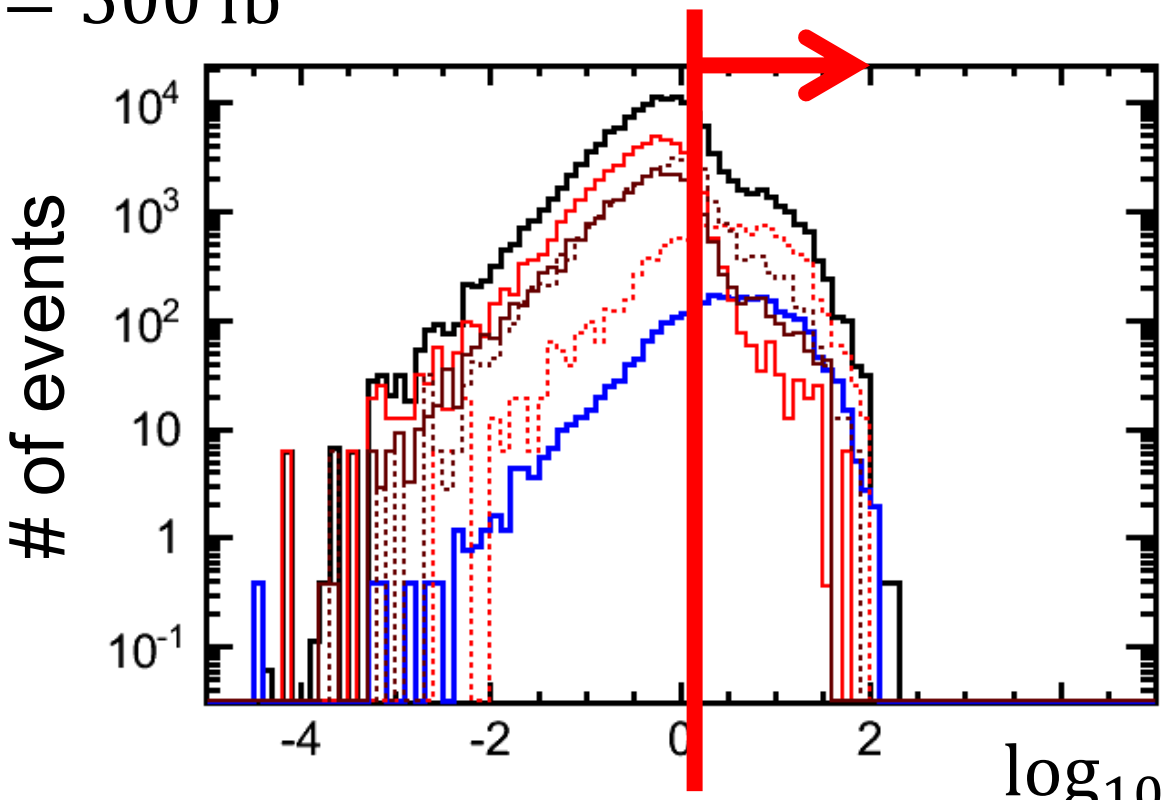
clustering based on tau mass

Most energetic $\tau^+$ and $\tau^-$ were combined as a Higgs boson.

--> suppress combinatorial background ($\gamma\gamma \rightarrow$ hadrons)

# Cut-based Analysis

$\int L\,dt = 500\ \mathrm{fb}^{-1}$




- all
- signal
- $\nu\nu\ell\ell$ bkg
- $\nu\nu\tau\ell$ bkg
- $\nu\nu\tau\tau$ bkg
- other 4f bkg

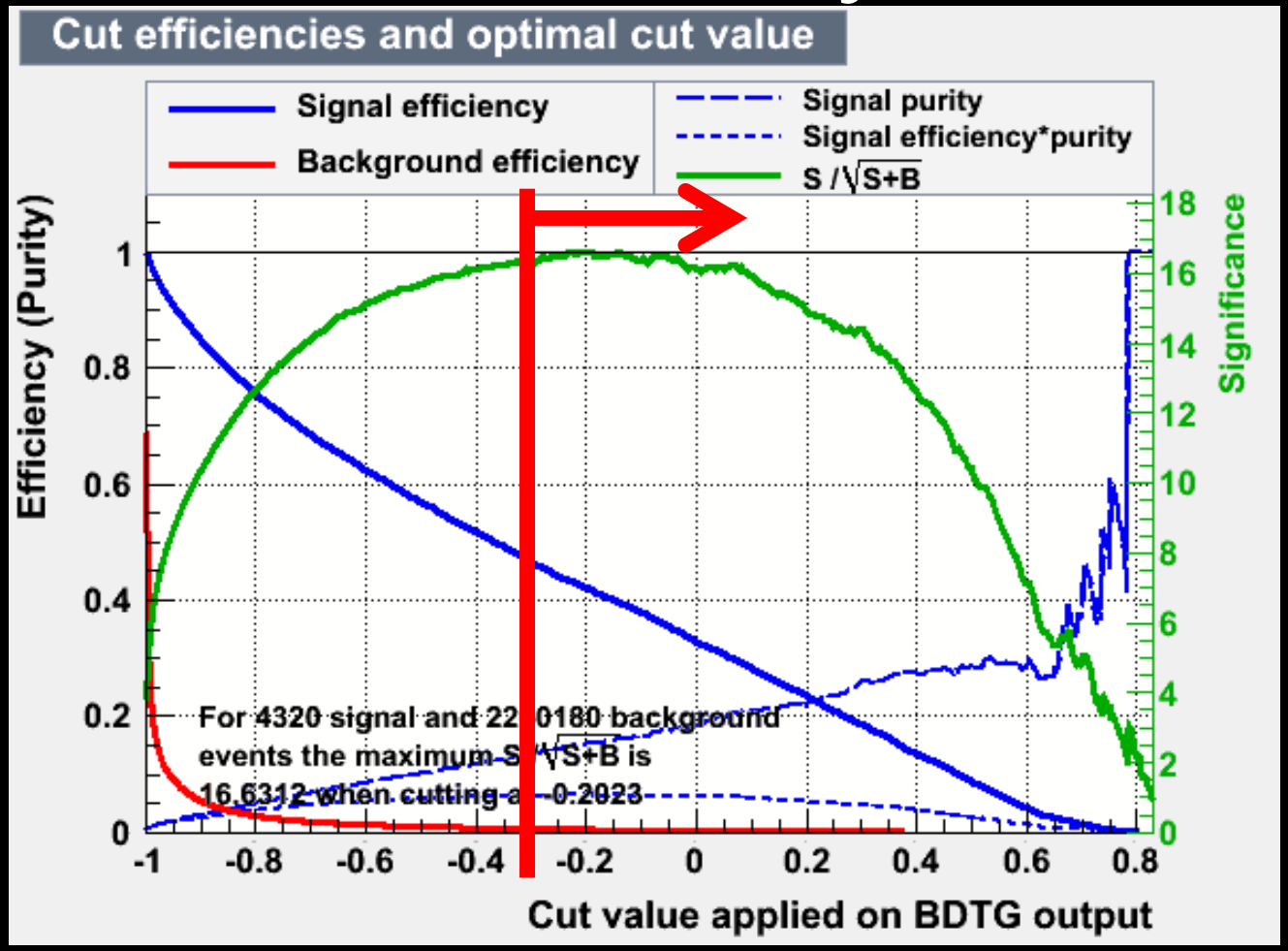
$(\ell = e, \mu)$

| | signal | 4f $\nu\nu\tau\tau$ | other SM bkg |
|---|---|---|---|
| No cut | 5401 | $1.452*10^5$ | $2.991*10^7$ |
| After cut | 1416 | 5963 | 3539 |

$$\frac{S}{\sqrt{S+B}} = 13.6\sigma$$

$$\frac{\Delta(\sigma\cdot\mathrm{Br})}{(\sigma\cdot\mathrm{Br})} = 7.4\%$$

# TMVA Analysis

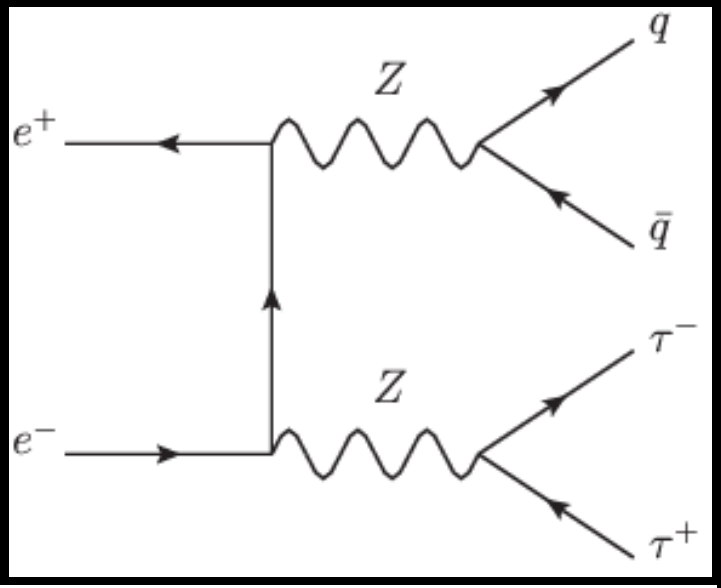



remained events: $N_{\mathrm{sig}} = 1824$, $N_{\mathrm{bkg}} = 10204$

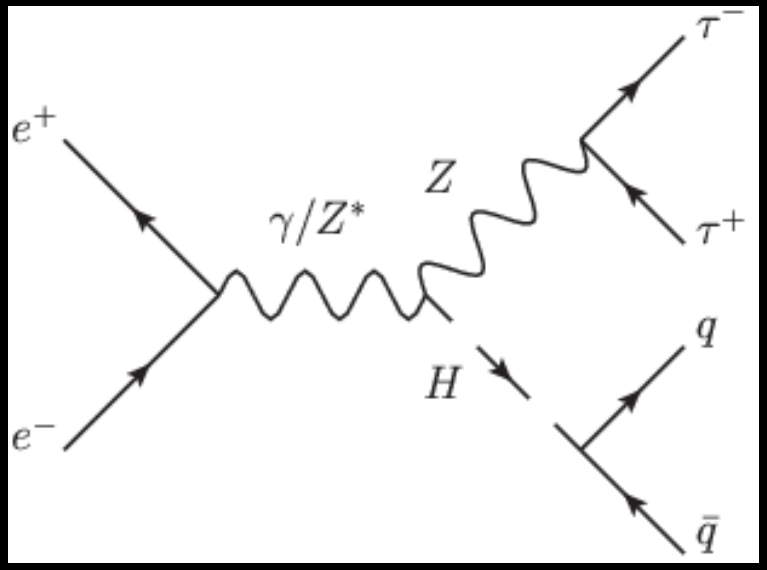
$\frac{S}{\sqrt{S+B}} = 16.6\sigma$, $\frac{\Delta(\sigma \cdot \mathrm{Br})}{(\sigma \cdot \mathrm{Br})} = \mathbf{6.0\%}$

# $q\bar{q}h$ @ 500 GeV

# Main Backgrounds

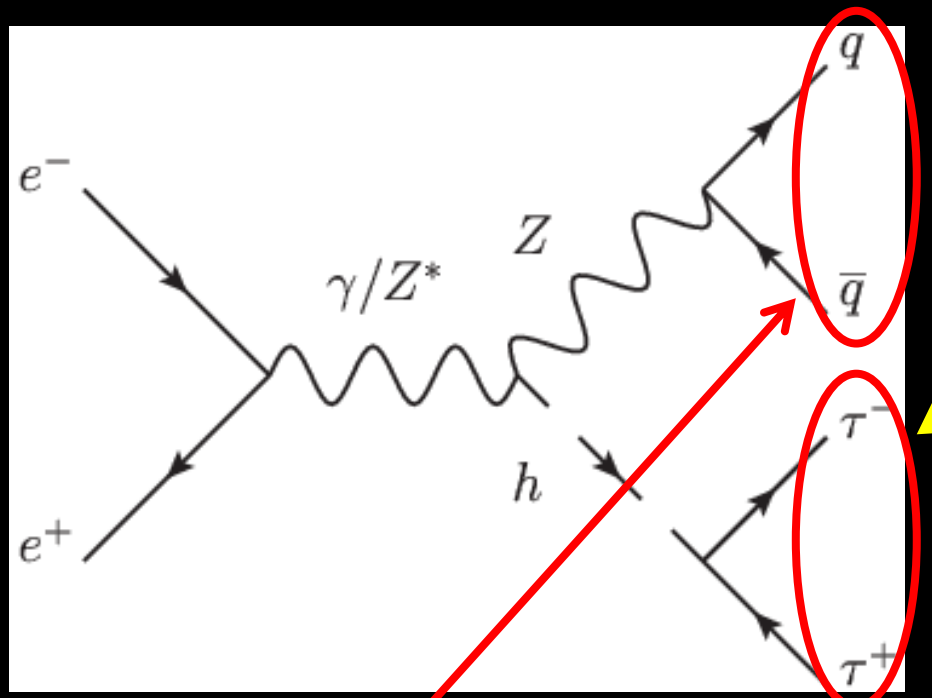



$e^+e^- \to ZZ \to q\bar{q}\tau^+\tau^-$
irreducible process




$e^+e^- \to Zh$
$\to (\tau^+\tau^-)(q\bar{q})$
mimic signal

# Reconstruction




(0) $k_t$ clustering

remove $\gamma\gamma \rightarrow$ hadrons

(1) tau & Higgs reco.

tau jet finder

clustering based on tau mass optimized in the presence of jet background

collinear approximation

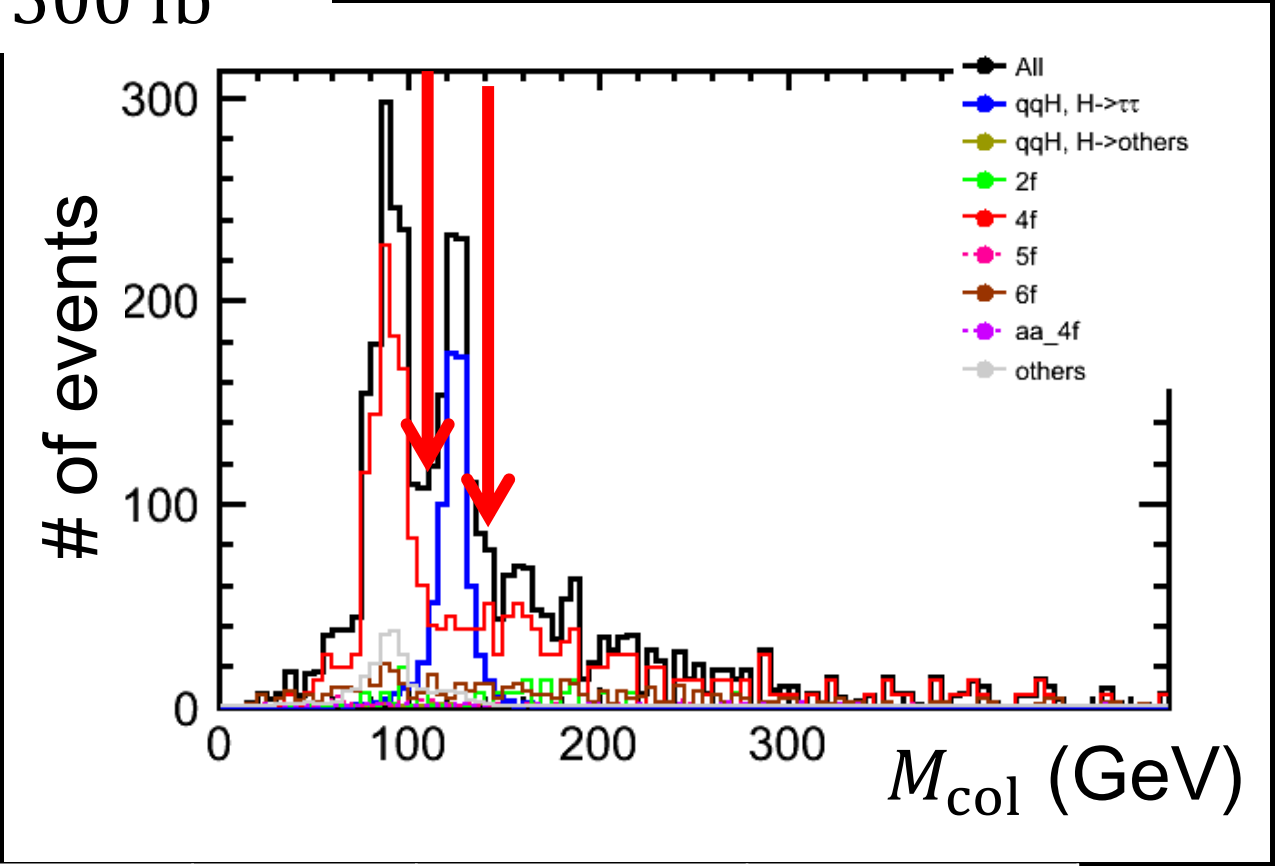
tau pair mass reconstruction

(2) $Z$ reco.

jet finder with Durham algorithm into 2 jets

$\int L\,dt = 500\ \mathrm{fb}^{-1}$

# Cut-based Analysis




all
signal
4f bkg

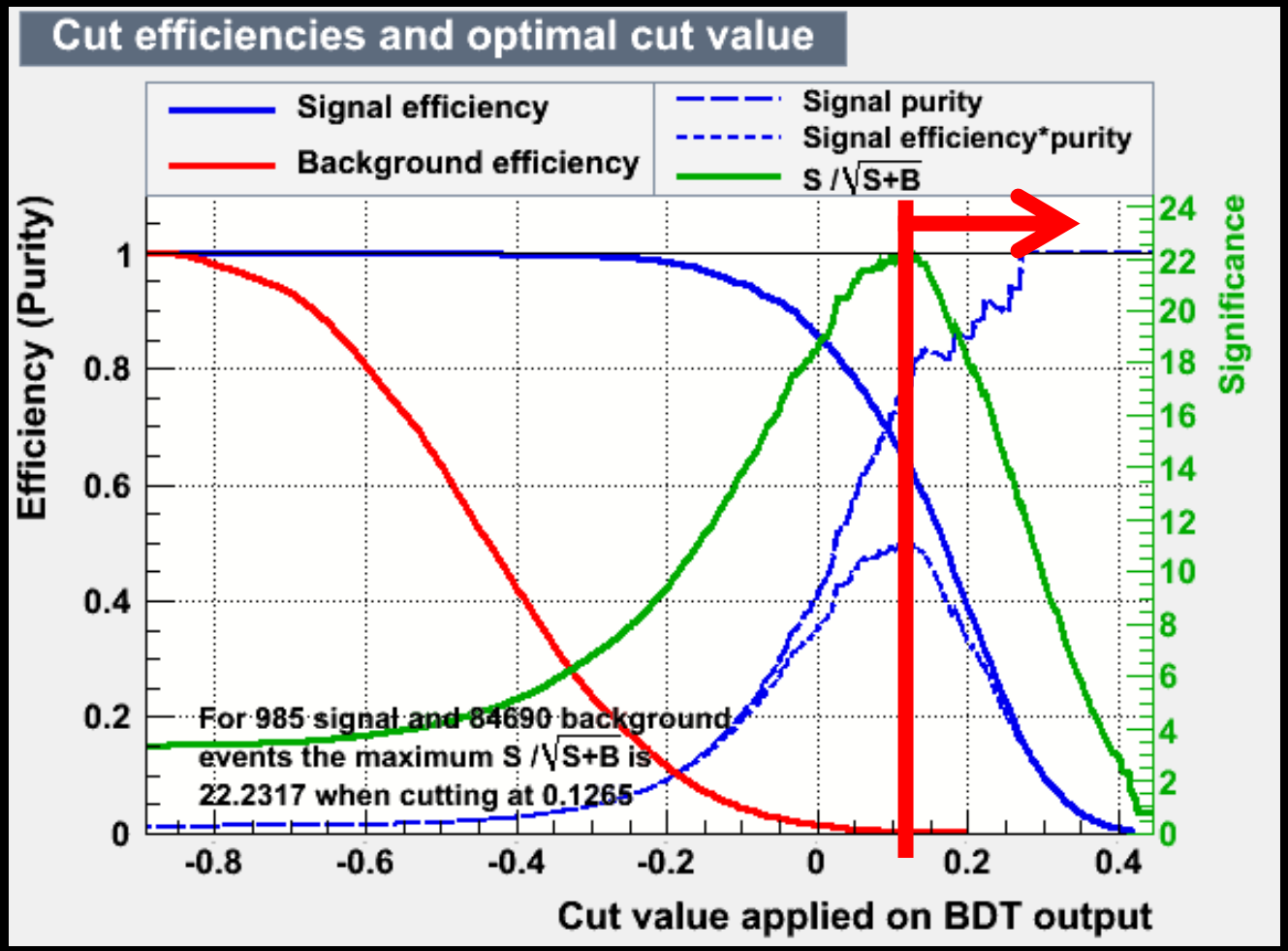
$M_{\mathrm{col}}$= tau pair mass w/ collinear approximation

| | signal | 4f | other SM bkg |
|---|---|---|---|
| No cut | 2158 | $1.598*10^7$ | $1.409*10^7$ |
| After cut | 560.7 | 155.8 | 80.04 |

$$\frac{S}{\sqrt{S+B}} = 19.9\sigma$$

$$\frac{\Delta(\sigma\cdot \mathrm{Br})}{(\sigma\cdot \mathrm{Br})} = \mathbf{5.0\%}$$

# TMVA Analysis




remained events: $N_{\mathrm{sig}} = 613.2$, $N_{\mathrm{bkg}} = 147.6$

$\frac{S}{\sqrt{S+B}} = 22.2\sigma$, $\frac{\Delta(\sigma \cdot \mathrm{Br})}{(\sigma \cdot \mathrm{Br})} = \mathbf{4.5\%}$

# Summary

We evaluated the precision of branching ratio of $h \to \tau^+\tau^-$ mode with ILD full detector simulation.

| $\sqrt{s}$ (GeV) | 250 | 500 | | 500 | |
|---|---|---|---|---|---|
| Analyzed mode | $q\bar{q}h, l^+l^-h$ | $q\bar{q}h$ | | $\nu\bar{\nu}h$ | |
| $\int L\,dt$ (fb$^{-1}$) | 250 | 500 | | 500 | |
| $\frac{\Delta(\sigma \cdot \mathrm{Br})}{(\sigma \cdot \mathrm{Br})}$ | 4.2%<br>Cut-based<br>Extrapolation from $M_h = 120$ GeV | 5.0%<br>Cut-based | 4.5%<br>TMVA | 7.4%<br>Cut-based | 6.0%<br>TMVA |

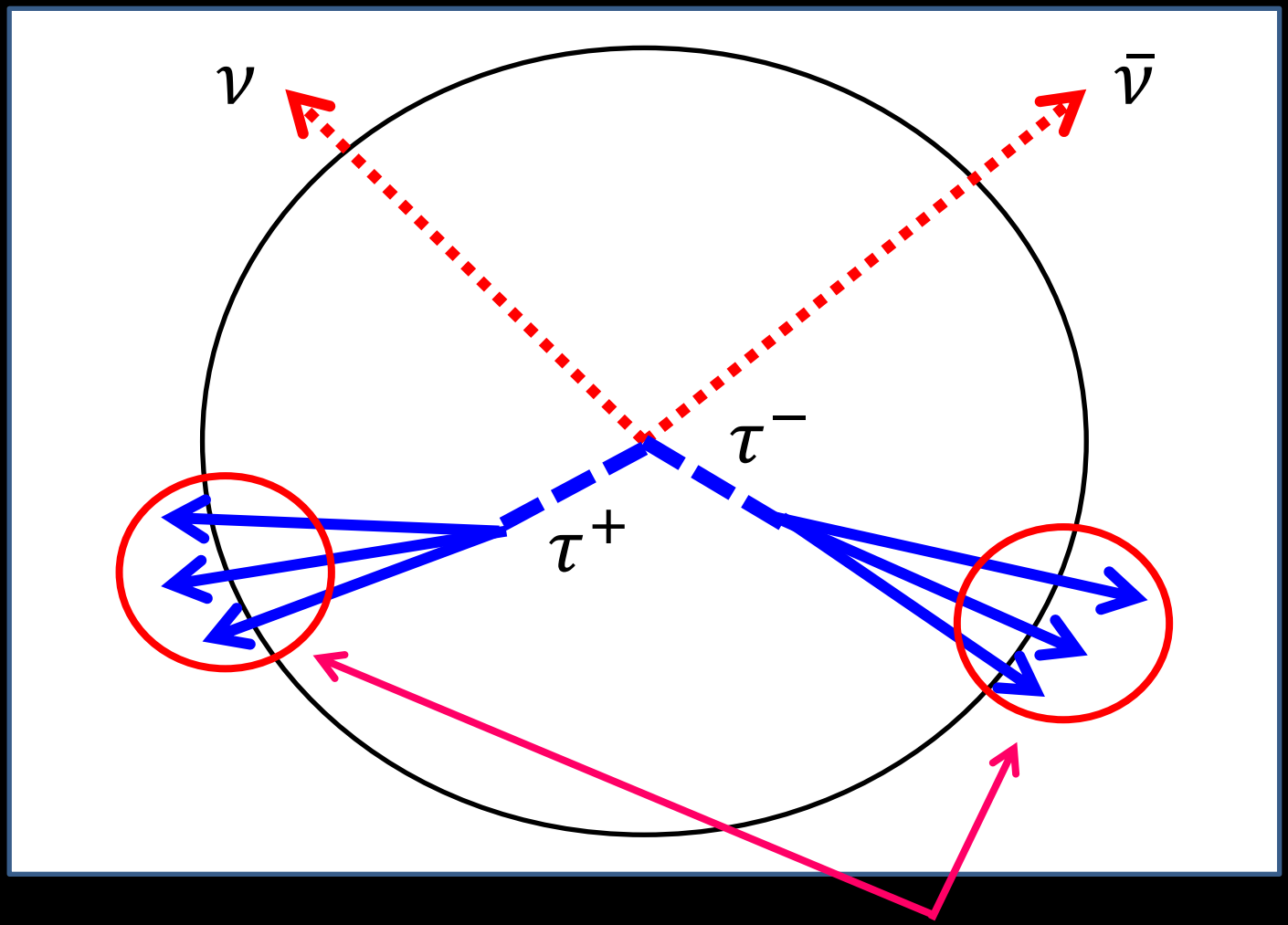
# Future Plans

- Include $\gamma\gamma \rightarrow$ 2f process
- More optimization in TMVA
- 500 GeV $l^+l^-h$ mode
- Re-do 250 GeV analysis with $M_h = 125$ GeV

# BACKUP SLIDES

$\nu\bar{\nu}h$

# Tau Reconstruction



# Cut-based Analysis: Cut Flow

Cut 0: # of $\tau^{+(-)} \geq 1$ (pre-selection)
Cut 1: # of tracks <= 6
Cut 2: $M_{\mathrm{vis}} < 135$
Cut 3: $E_{\mathrm{vis}} < 245$
Cut 4: $P_t > 25$
Cut 5: $|\cos\theta_{\mathrm{miss}}| < 0.91$
Cut 6: thrust < 0.99
Cut 7: $M_{\tau^+\tau^-} < 120$
Cut 8: $-0.78 < \cos\theta_{\tau^+\tau^-} < 0.54$
Cut 9: $\cos\theta_{\mathrm{acop}} < 0.99$
Cut 10: $\log_{10}|\min d_0\mathrm{sig}| > 0.3$
Cut 11: $\log_{10}|\min z_0\mathrm{sig}| > 0$

# Cut Table

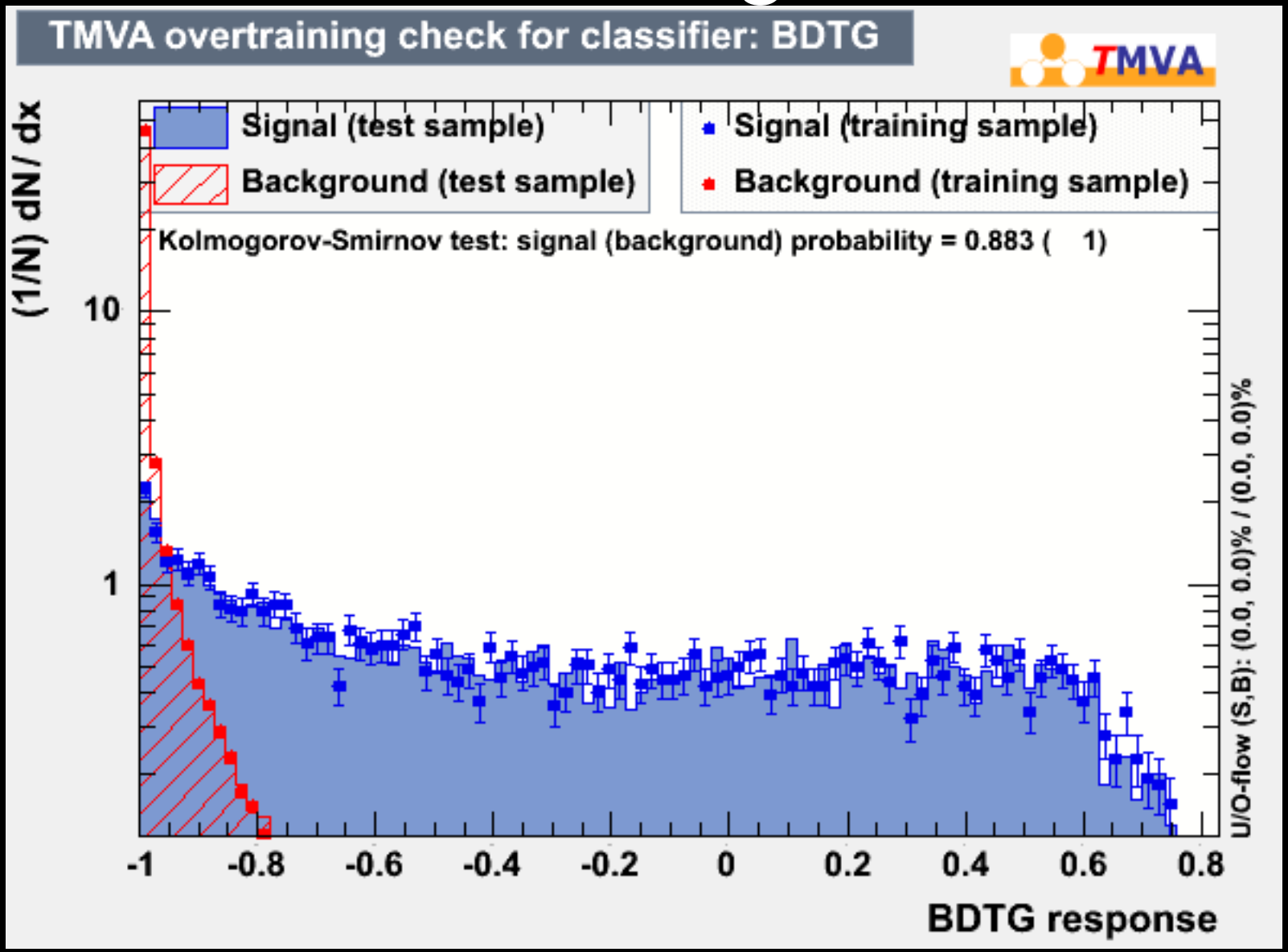
| | $\nu\nu h$ $h \to \tau\tau$ | $\nu\nu h$ $h \nrightarrow \tau\tau$ | 2f | 4f $\nu\nu\tau\tau$ | 4f $\nu\nu\ell\ell$ | 4f $\nu\nu\tau\ell$ | 4f others | 5f | 6f | aa_4f | $qqh$ $llh$ | signi. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No Cut | 5401 | 7.954e04 | 1.319e07 | 1.452e05 | 9.450e05 | 6.309e05 | 1.426e07 | 6.985e04 | 5.888e05 | 1.041e05 | 4.372e04 | 0.985 |
| pre-sel | 4676 | 6062 | 3.973e06 | 1.070e05 | 6.686e05 | 4.616e05 | 3.085e06 | 2.093e04 | 2.333e04 | 4.132e04 | 2650 | 1.61 |
| # of tracks | 4274 | 2461 | 2.649e06 | 9.896e04 | 6.522e05 | 4.404e05 | 1.364e06 | 1.123e04 | 7035 | 2.782e04 | 1126 | 1.86 |
| $M_{\mathrm{vis}}$ | 4263 | 2438 | 8.235e05 | 5.660e04 | 2.064e05 | 1.492e05 | 7.964e05 | 7244 | 2775 | 2.476e04 | 262.9 | 2.96 |
| $E_{\mathrm{vis}}$ | 4259 | 2433 | 6.226e05 | 5.651e04 | 1.833e05 | 1.423e05 | 6.720e05 | 6963 | 2749 | 2.388e04 | 233.7 | 3.25 |
| $P_t$ | 3996 | 2183 | 4.407e05 | 4.611e04 | 1.626e05 | 1.314e05 | 2.323e05 | 5281 | 2696 | 9364 | 233.1 | 3.92 |
| $\cos\theta_{\mathrm{miss}}$ | 3419 | 1946 | 7.240e04 | 3.283e04 | 9.290e04 | 7.660e04 | 5.280e04 | 2916 | 2063 | 4665 | 176.7 | 5.84 |
| thrust | 3258 | 1822 | 3.089e04 | 2.453e04 | 8.466e04 | 5.960e04 | 4.895e04 | 2824 | 1983 | 4444 | 173.9 | 6.35 |
| $M_{\tau\tau}$ | 3242 | 1810 | 2.928e04 | 2.265e04 | 7.856e04 | 5.272e04 | 4.792e04 | 2658 | 1796 | 4305 | 169.1 | 6.55 |
| $\cos\theta_{\tau\tau}$ | 2749 | 878.5 | 1.395e04 | 1.230e04 | 4.908e04 | 3.396e04 | 2.566e04 | 1781 | 1248 | 2810 | 64.38 | 7.23 |
| $\cos\theta_{\mathrm{acop}}$ | 2663 | 865.4 | 6600 | 1.192e04 | 4.771e04 | 3.267e04 | 2.498e04 | 1739 | 1228 | 2745 | 63.18 | 7.3 |
| $d_0\mathrm{sig}$ | 1672 | 71.14 | 652.1 | 7096 | 1366 | 4848 | 1905 | 155.0 | 135.1 | 241.0 | 11.41 | 12.4 |
| $z_0\mathrm{sig}$ | **1416** | 36.92 | 475.3 | **5963** | 228.6 | 1607 | 904.2 | 84.43 | 77.09 | 117.7 | 7.617 | **13.6** |

# TMVA Analysis: Inputs

# of tracks, $M_{\mathrm{vis}}$, $P_t$, thrust, $\cos\theta_{\mathrm{miss}}$, $M_{\tau^+\tau^-}$, $E_{\tau^+\tau^-}$, $\cos\theta_{\tau^+\tau^-}$, $\cos\theta_{\mathrm{acop}}$, $\log_{10}|\min d_0\mathrm{sig}|$, $\log_{10}|\min z_0\mathrm{sig}|$

Pre-cuts before TMVA analysis:
# of $\tau^+(\tau^-) \geq 1$, # of tracks <= 6, $M_{\mathrm{vis}} < 160, P_t < 250$

# TMVA Training Results



$q\bar{q}h$

by T. Suehara

# TaJet finder (1)

High-purity tau tagging
in presence of jet background

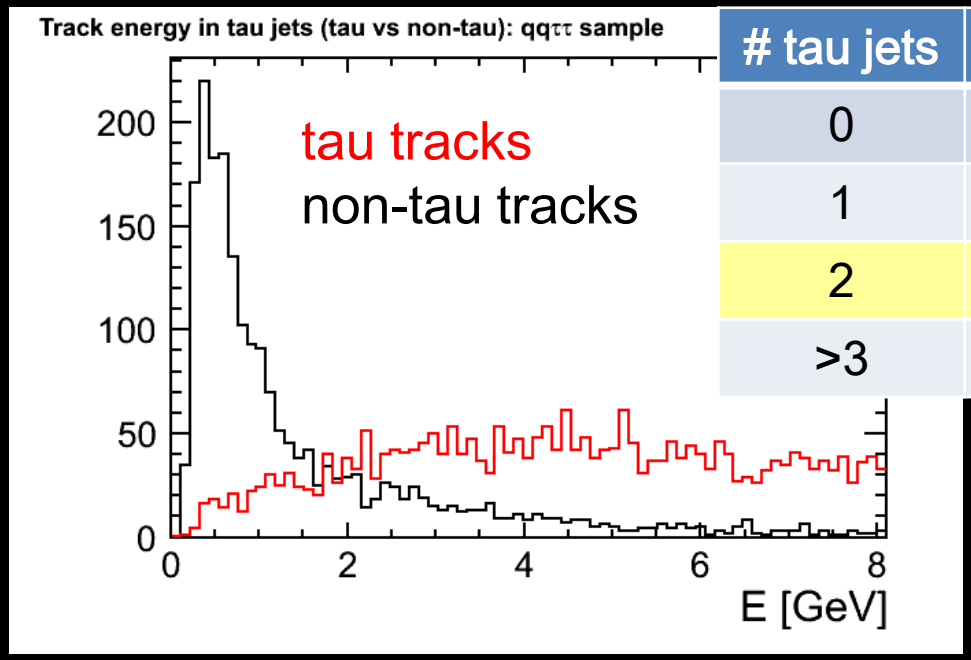
1. Order charged tracks by largest energy
2. Select the first track
3. Combine neighboring particles -> “Tau Jet”
   - Combined mass < 2 GeV && cosθ w.r.t. jet axis > 0.98
4. Tau selection (tuned for rejecting qq background)
   1. Tau Jet energy > 3 GeV
   2. Veto >=3 prong + neutrals (> 1 GeV)
   3. Cone energy ($E_{cone} < 0.1E_{taujet}$) with $\cos\theta_{cone} = 0.9$

| ZZ -> qqττ 250 GeV, 13600 taus | 1-prong | | 3-prong wo/ neutral | | 3-prong w/ neutral | |
|---|---|---|---|---|---|---|
| | tau | non-tau | tau | non-tau | tau | non-tau |
| No cut | 10326 | 43286 | 716 | 1616 | 777 | 4280 |
| $E_{taujet} > 3$ | 8679 | 7145 | 708 | 1304 | 742 | 4244 |
| $E_{cone} < 0.5E_{taujet}$ | 7170 | 1009 | 621 | 181 | 681 | 1813 |
| $E_{cone} < 0.2E_{taujet}$ | 6455 | 446 | 567 | 64 | 616 | 1020 |
| $E_{cone} < 0.1E_{taujet}$ | 6001 | 254 | 527 | 30 | 570 | 620 |

by T. Suehara

# TaJet finder (2)

5. Jet charge recovery (for better efficiency)
   - Tracks with energy < 2 GeV are detached one by one until tau jet has 1 or 3 tracks and sum charge is +1 or -1
   - Jet is rejected if above condition cannot be satisfied after detaching all < 2 GeV tracks
6. Return to 2. (previous page) with the remaining tracks
   - Stop after all E > 2 GeV tracks have been processed




| # tau jets | $qq\tau\tau$ | $qqlv$ |
|---|---|---|
| 0 | 27.1% | 47.6% |
| 1 | 36.3% | 46.6% |
| 2 | 34.0% | 5.4% |
| >3 | 2.4% | 0.3% |

efficiency:
58.1% (1-prong)
73.6% (3-prong)

purity of tau in $qq\tau\tau$:
94.2% (overall)
96.5% (# tau jets == 2)

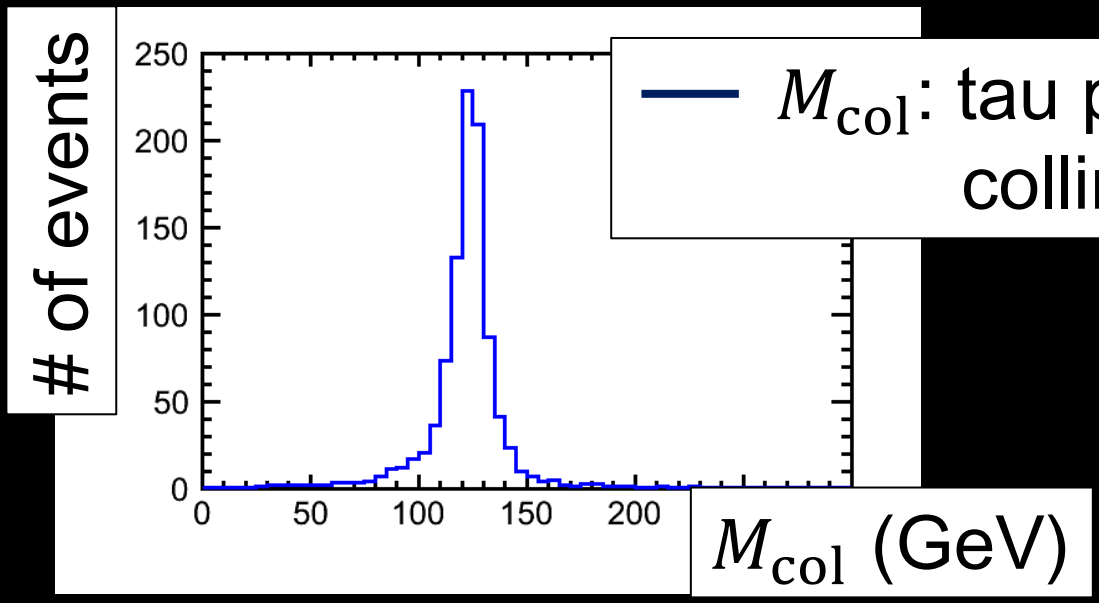
# Collinear Approximation

## Method of reconstructing tau pair mass ($M_{\tau^+\tau^-} = M_h$)

Assumptions:

- visible tau decay products and neutrinos are collinear
- contribution of missing momentum comes only from neutrinos of tau decay

We use the knowledge of the initial 4-momentum at the ILC.



# Cut-based Analysis: Cut Flow

Cut 0: # of $q$ == 2, # of $\tau^{+(-)}$== 1 (pre-selection)
Cut 1: # of tracks >= 9
Cut 2: $E_{\mathrm{vis}} < 475$
Cut 3: $P_t > 165$
Cut 4: thrust < 0.93
Cut 5: $|\cos\theta_{\mathrm{miss}}| < 0.92$
Cut 6: $55 < M_Z\left(M_{q\bar{q}}\right) < 145$
Cut 7: $E_Z\left(E_{q\bar{q}}\right) > 180$
Cut 8: $\cos\theta_{q\bar{q}} > -0.94$
Cut 9: $M_{\tau^+\tau^-} < 120$
Cut 10: $\cos\theta_{\tau^+\tau^-} < 0.59$
Cut 11: $\cos\theta_{\mathrm{acop}} < 0.91$
Cut 12: $\log_{10}|d_0\mathrm{sig}(\tau^+)| + \log_{10}|d_0\mathrm{sig}(\tau^-)| > 0$
Cut 13: $110 < M_{\mathrm{col}} < 140$
Cut 14: $195 < E_{\mathrm{col}} < 290$
Cut 15: $M_{\mathrm{recoil}} > 50$

| | $\nu\nu h$ $h \to \tau\tau$ | $\nu\nu h$ $h \nrightarrow \tau\tau$ | 2f | 4f | 5f | 6f | aa_4f | $\nu\nu h$ $llh$ | signi. |
|---|---|---|---|---|---|---|---|---|---|
| No Cut | 2158 | 3.139e04 | 1.320e07 | 1.598e07 | 6.895e04 | 5.888e05 | 1.041e05 | 9.511e04 | 0.394 |
| pre-sel | 1004 | 425.3 | 1.046e06 | 9.992e05 | 9326 | 3.603e04 | 1.278e04 | 7404 | 0.691 |
| # of tracks | 1003 | 425.3 | 1.383e05 | 3.566e05 | 7150 | 3.518e04 | 6204 | 5723 | 1.35 |
| $E_{\mathrm{vis}}$ | 988.4 | 399.8 | 8.975e04 | 2.980e05 | 6739 | 3.474e04 | 6053 | 3843 | 1.49 |
| $P_t$ | 932.2 | 366.8 | 2.975e04 | 1.268e05 | 4043 | 3.020e04 | 1858 | 2851 | 2.1 |
| thrust | 881.6 | 316.2 | 7776 | 6.106e04 | 3949 | 2.989e04 | 1803 | 2658 | 2.68 |
| $\cos\theta_{\mathrm{miss}}$ | 817.0 | 281.1 | 2304 | 3.819e04 | 2405 | 2.647e04 | 978.8 | 1711 | 3.02 |
| $M_Z(M_{qq})$ | 774.2 | 226.1 | 462.1 | 1.875e04 | 1895 | 1.078e04 | 792.1 | 1543 | 4.13 |
| $E_Z(E_{qq})$ | 728.6 | 210.6 | 258.1 | 1.127e04 | 534.4 | 2675 | 184.3 | 1080 | 5.6 |
| $\cos\theta_{qq}$ | 728.0 | 210.3 | 251.3 | 1.119e04 | 534.4 | 2669 | 184.3 | 1079 | 5.61 |
| $M_{\tau\tau}$ | 726.6 | 208.6 | 194.7 | 9516 | 306.2 | 2121 | 103.0 | 1008 | 6.1 |
| $\cos\theta_{\tau\tau}$ | 724.2 | 95.36 | 180.7 | 6137 | 240.9 | 1717 | 79.22 | 369.5 | 7.41 |
| $\cos\theta_{\mathrm{acop}}$ | 712.2 | 89.80 | 160.7 | 5254 | 199.1 | 1452 | 64.33 | 355.9 | 7.82 |
| $d_0\mathrm{sig}$ | 683.9 | 48.26 | 153.6 | 3121 | 89.09 | 773.8 | 35.69 | 238.2 | 9.54 |
| $M_{\mathrm{col}}$ | 584.1 | 7.020 | 7.189 | 237.6 | 4.800 | 54.89 | 1.975 | 34.22 | 19.1 |
| $E_{\mathrm{col}}$ | 572.1 | 5.850 | 7.189 | 181.0 | 3.082 | 32.27 | 0 | 32.82 | 19.8 |
| $M_{\mathrm{recoil}}$ | 560.7 | 5.850 | 7.189 | 155.8 | 3.082 | 32.27 | 0 | 31.66 | 19.9 |

# TMVA Analysis: Inputs

# of tracks, $M_{\mathrm{vis}}$, $P_t$, thrust, $\cos\theta_{\mathrm{miss}}$,
$M_Z(M_{q\bar{q}})$, $E_Z(E_{q\bar{q}})$, $\cos\theta_{q\bar{q}}$,
$M_{\tau^+\tau^-}$, $E_{\tau^+\tau^-}$, $\cos\theta_{\tau^+\tau^-}$, $\cos\theta_{\mathrm{acop}}$,
$\log_{10}|d_0\mathrm{sig}(\tau^+)| + \log_{10}|d_0\mathrm{sig}(\tau^-)|$,
$\log_{10}|z_0\mathrm{sig}(\tau^+)| + \log_{10}|z_0\mathrm{sig}(\tau^-)|$,
$M_{\mathrm{col}}$, $E_{\mathrm{col}}$, $M_{\mathrm{recoil}}$

Pre-cuts before TMVA analysis:
# of $q = 2$, # of $\tau^+(\tau^-) = 1$, 9 <= # of tracks <= 55,
$100 < M_{\mathrm{vis}} < 500$, $P_t > 80$, thrust < 0.98,
$15 < M_{q\bar{q}}(M_Z) < 400$, $E_{q\bar{q}}(E_Z) > 90$,
$M_{\tau^+\tau^-} < 140$, $E_{\tau^+\tau^-} > 15$, $M_{\mathrm{col}} < 300$, $100 < E_{\mathrm{col}} < 350$

# TMVA Training Results