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

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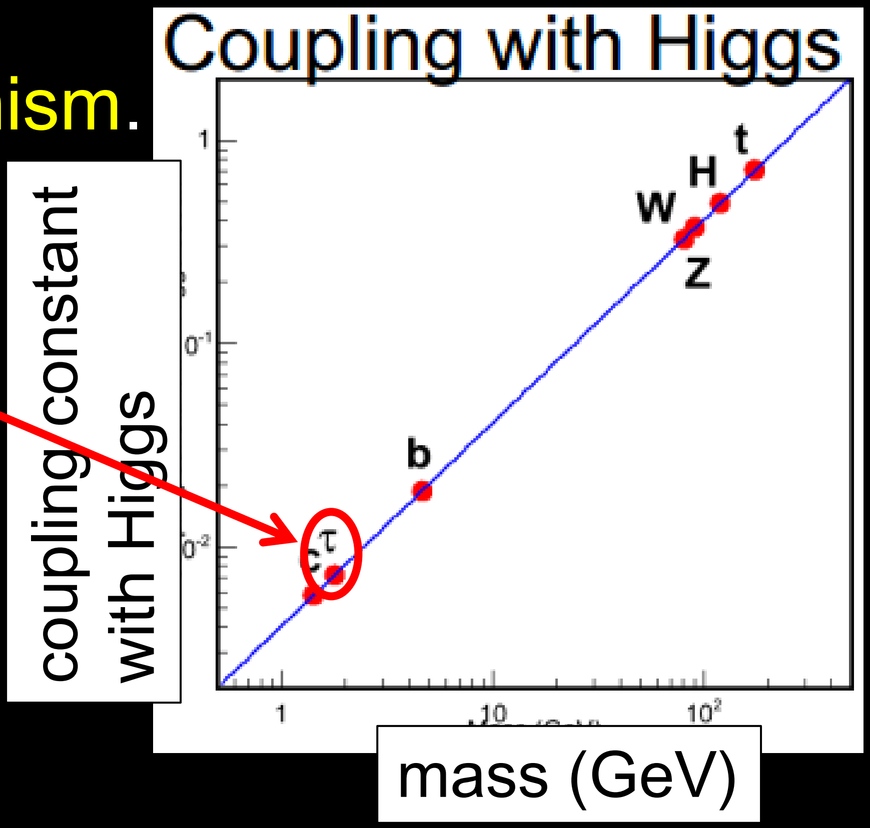
Introduction

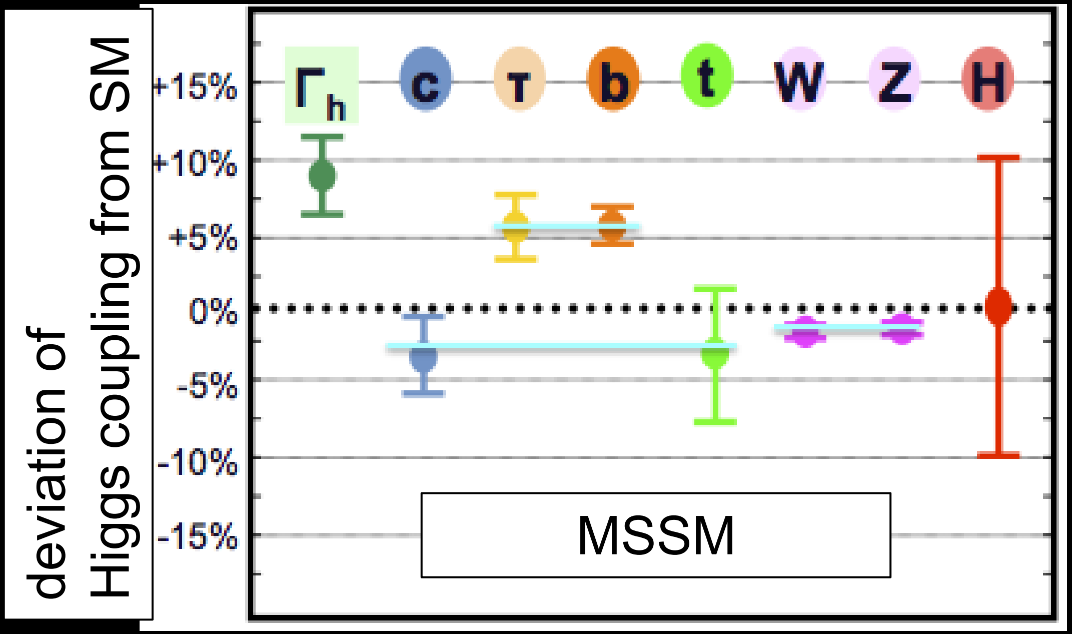
Since the discovery of Higgs boson, the investigation of its properties has become one of the most important themes in particle physics, especially the verification of the mass generation mechanism.

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.

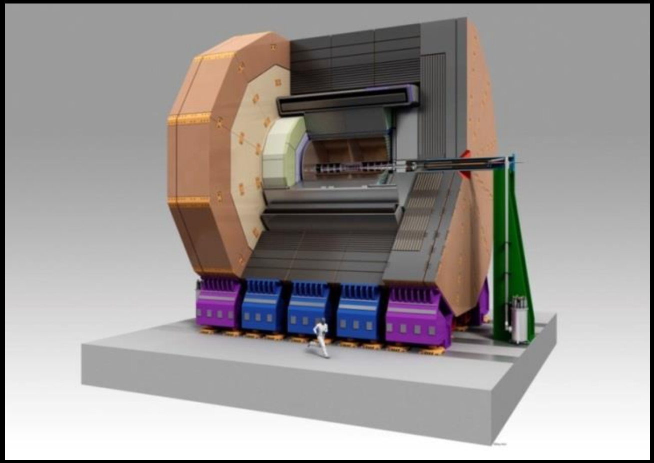
Target of This Study

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.

↓

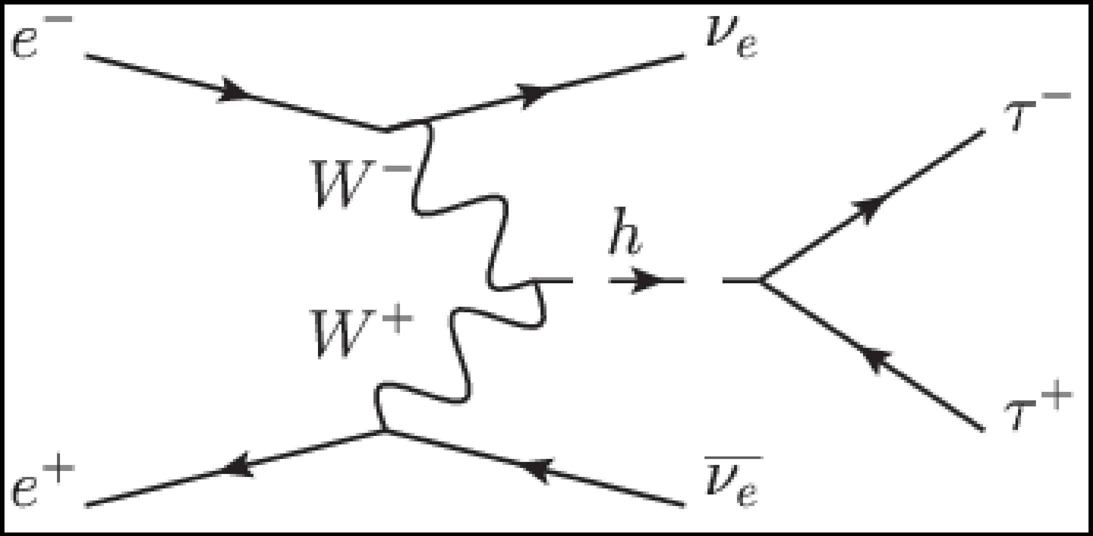
talked at
ECFA 2013 @ DESY



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

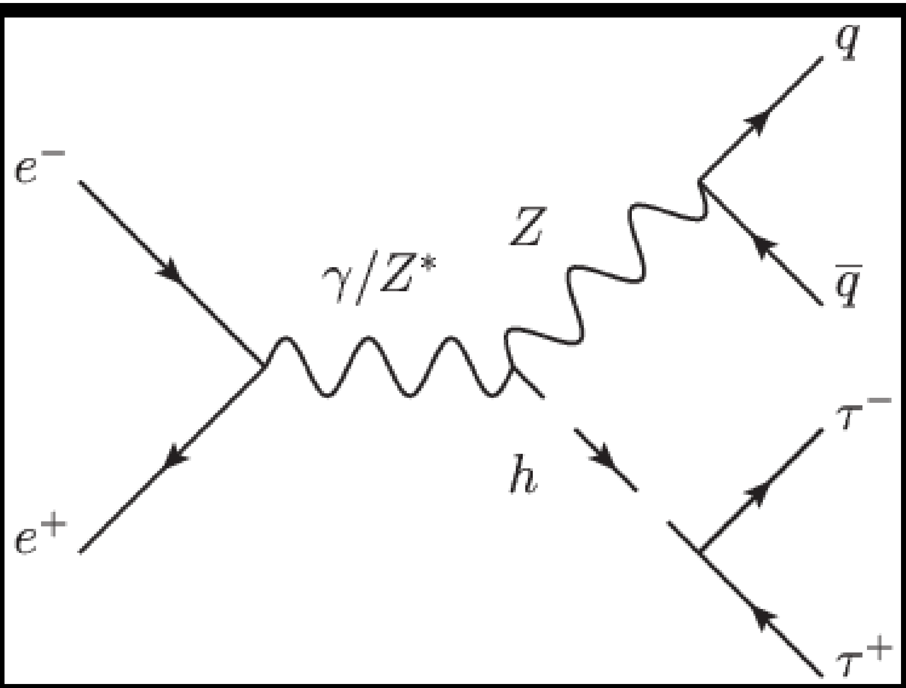
Signals



WW-fusion

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

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



Higgs-strahlung

$e^+e^- \to Zh$

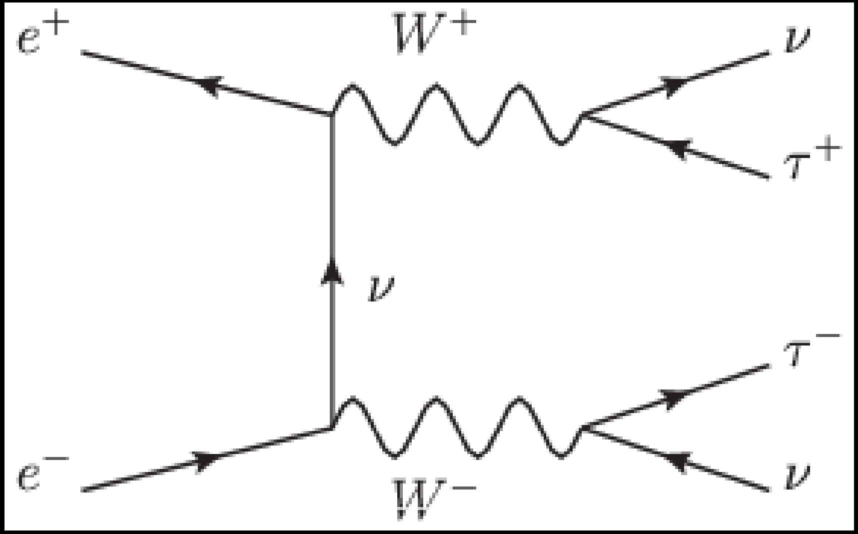
w/ $Z \to q\bar{q}, h \to \tau^+\tau^-$

Beam-induced Backgrounds

- We included the $\gamma\gamma$ 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.

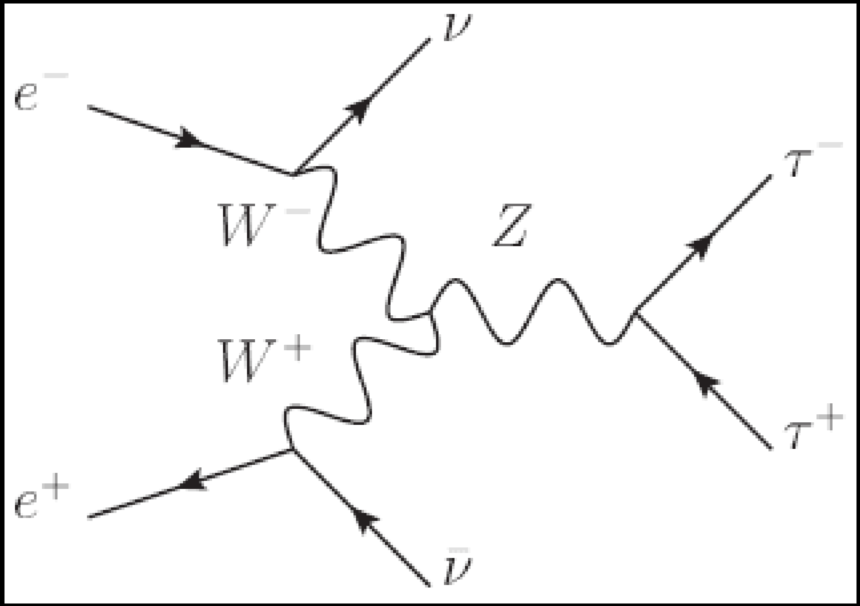
$\nu\bar{\nu}h$ @ 500 GeV

Main Backgrounds



$$e^+e^- \to W^+W^-(ZZ)$$
$$\to \nu\nu\tau^+\tau^-$$

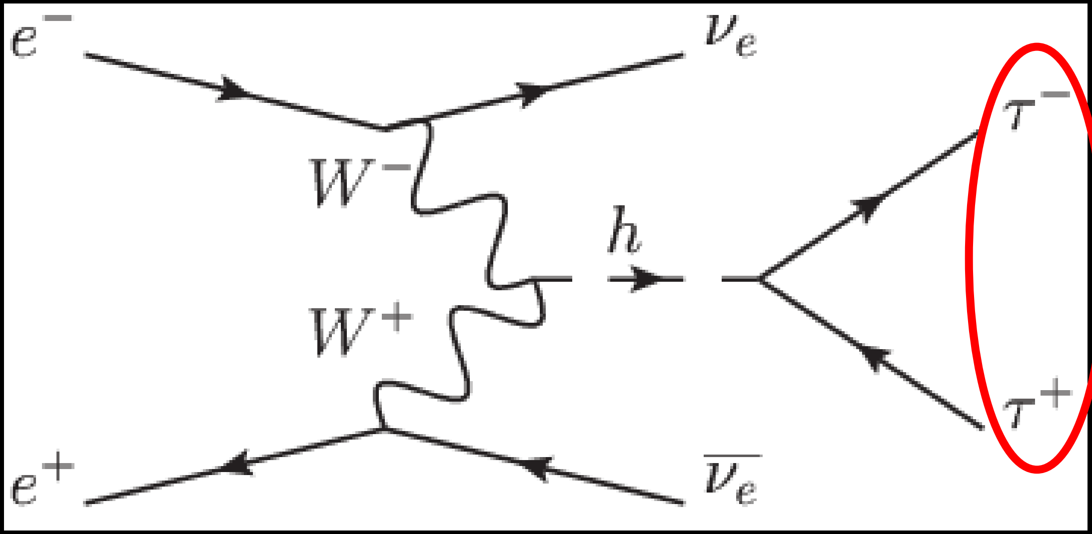
irreducible process



$$e^+e^- \to \nu\bar{\nu}Z \to \nu\bar{\nu}\tau^+\tau^-$$

irreducible process

Reconstruction



(1)

(0) k_t clustering

remove beam-induced backgrounds

(1) tau reco.

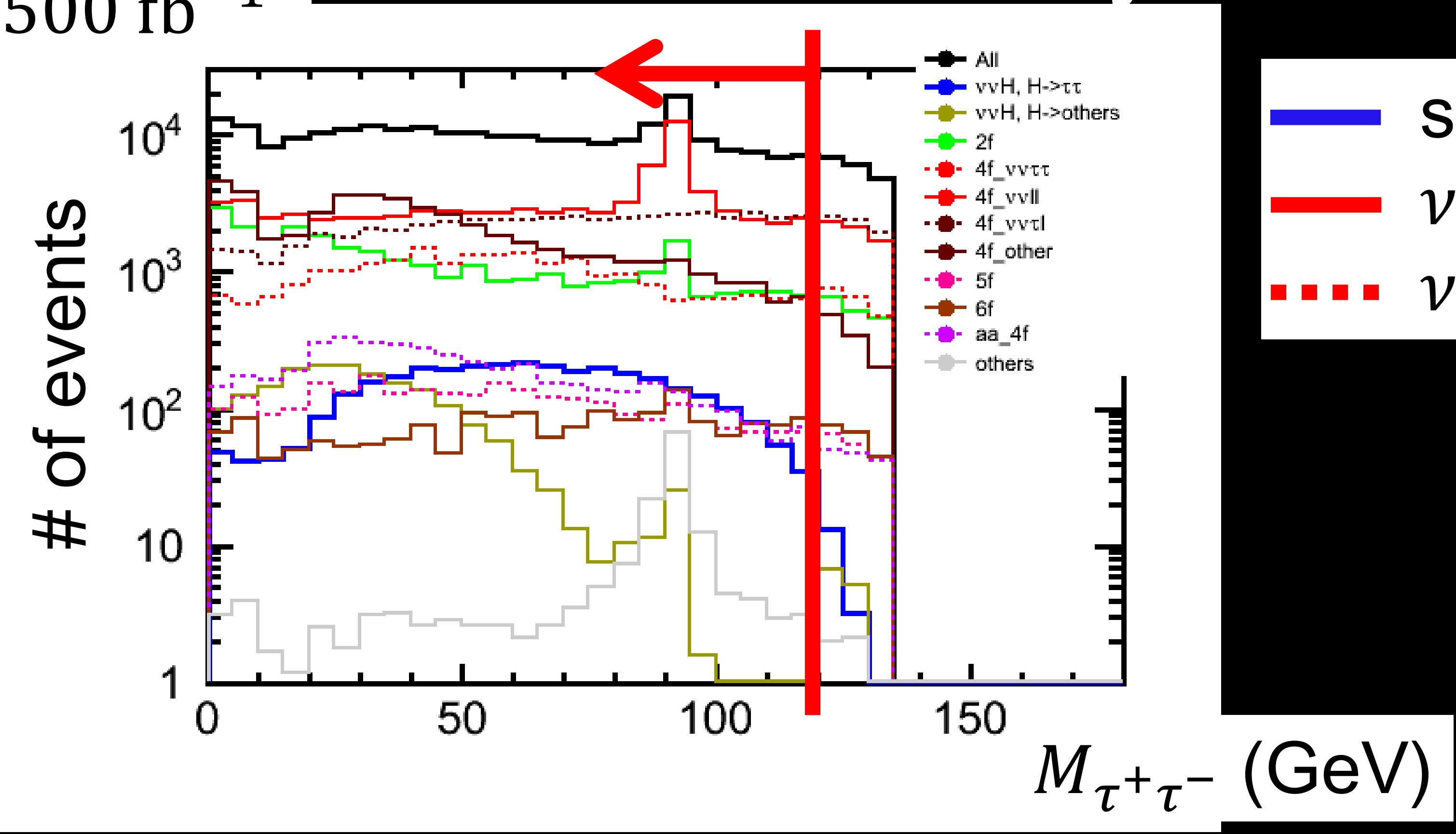
clustering based on tau mass

Most energetic τ^+ and τ^- were combined as a Higgs boson.

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

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

Cut-based Analysis

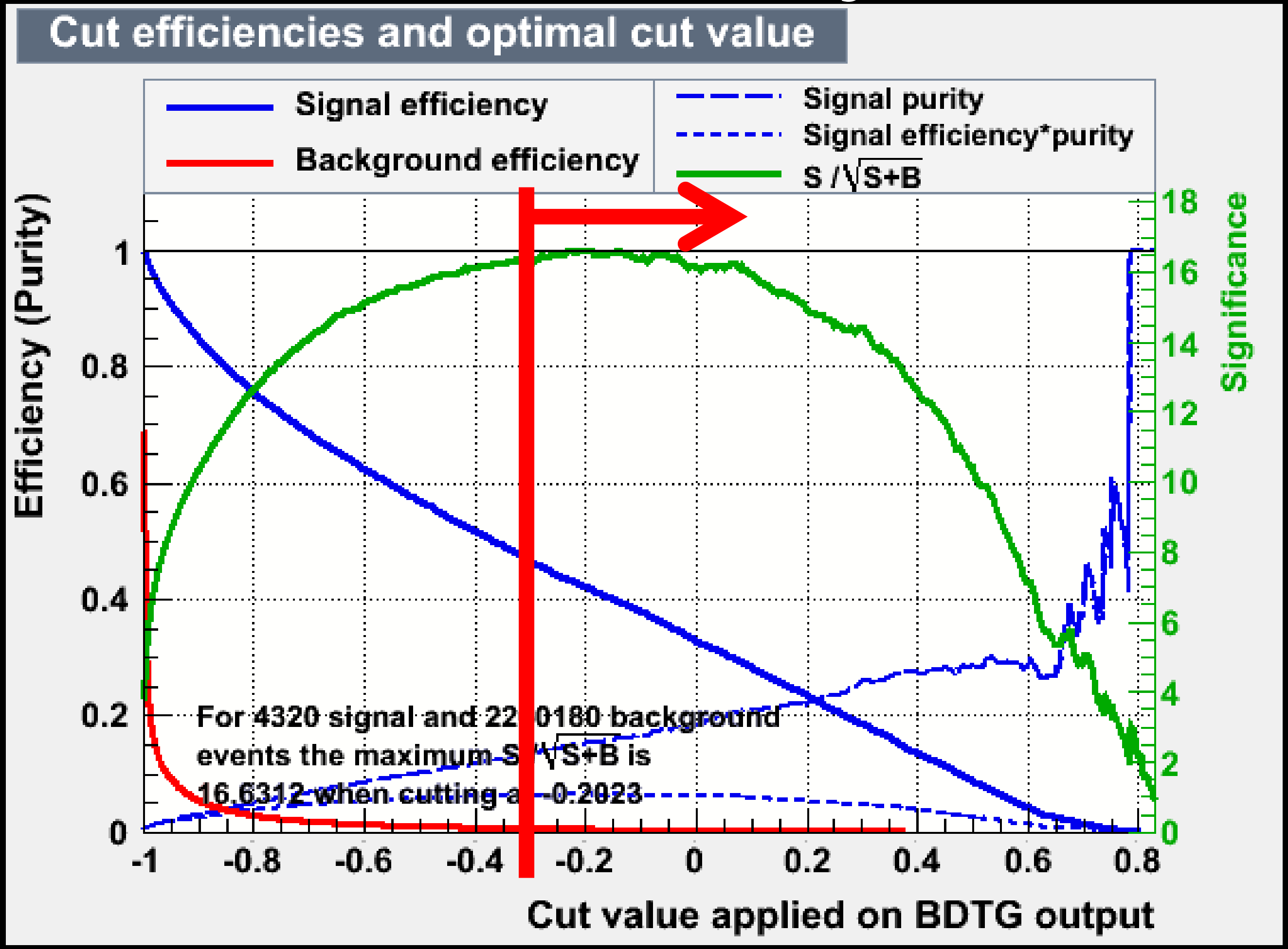


	signal	4f $\nu\nu\tau\tau$	other SM bkg
No cut	5401	1.452*10^5	2.991*10^7
After cut	**1416**	5963	3539

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

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

TMVA Analysis

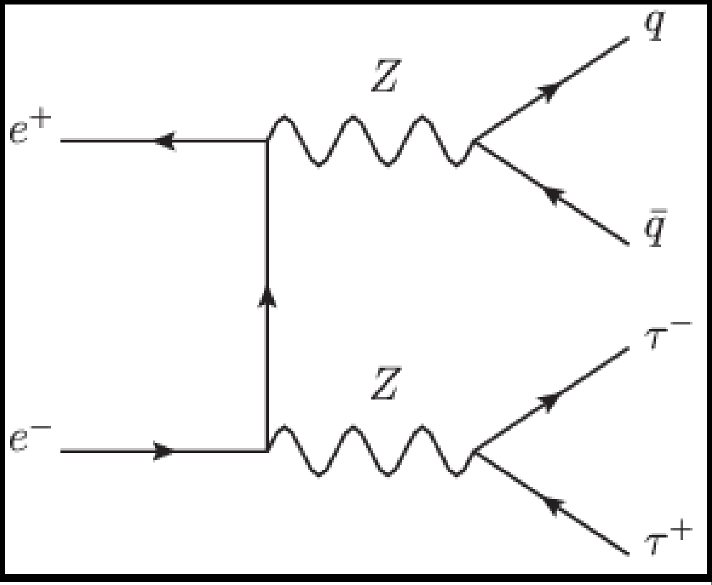


remained events: $N_{\text{sig}} = 1824$, $N_{\text{bkg}} = 10204$

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

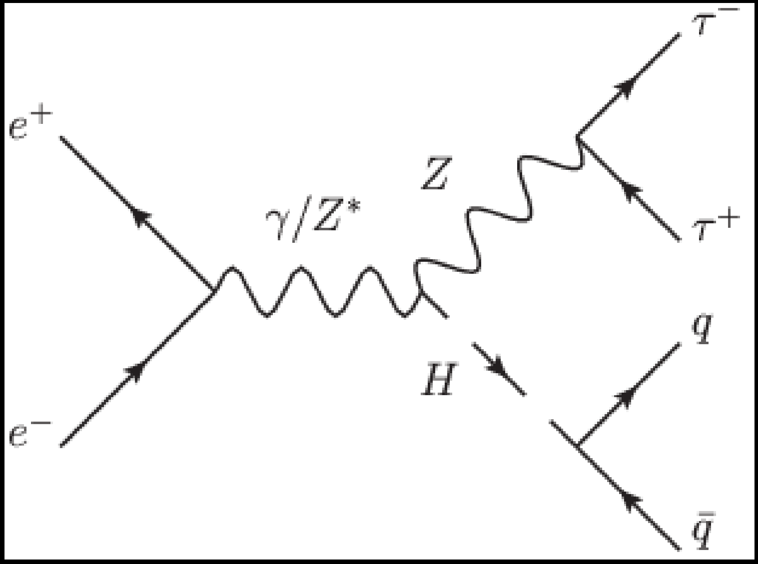
$q\bar{q}h$ @ 500 GeV

Main Backgrounds



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

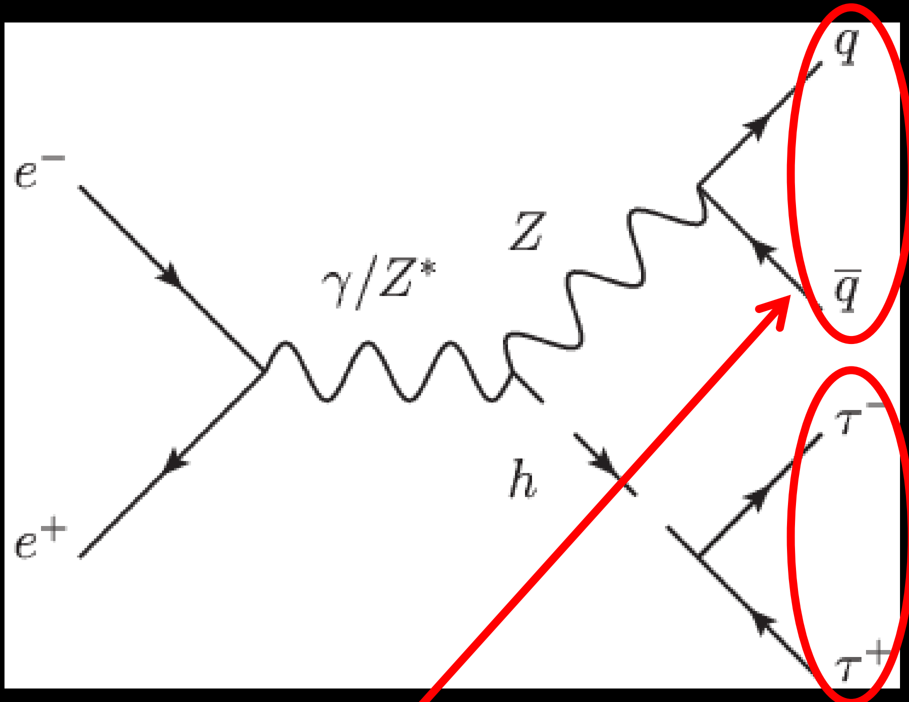
irreducible process



$e^+e^- \to Zh \to \tau^+\tau^-q\bar{q}$

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

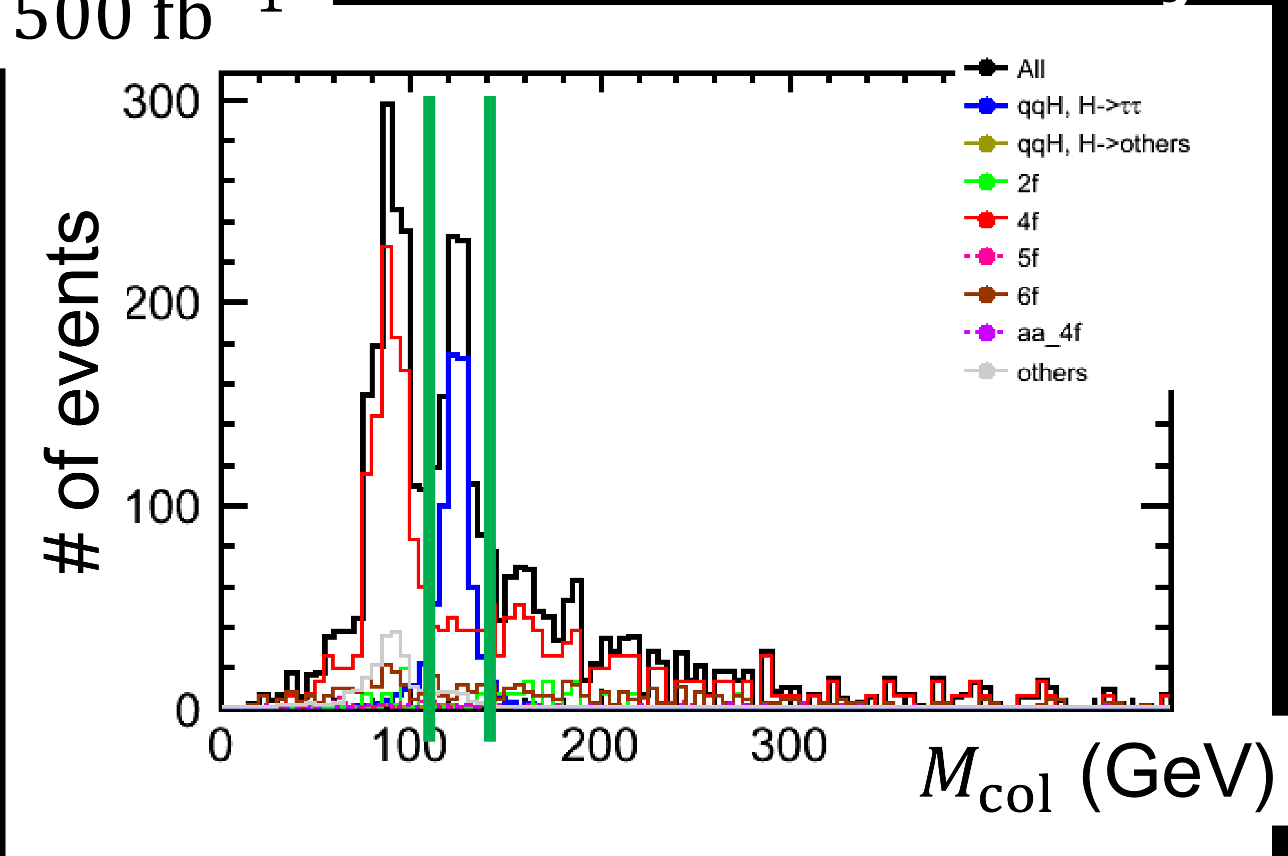
tau pair mass reconstruction

(2) Z reco.

jet finder with Durham algorithm into 2 jets

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

Cut-based Analysis



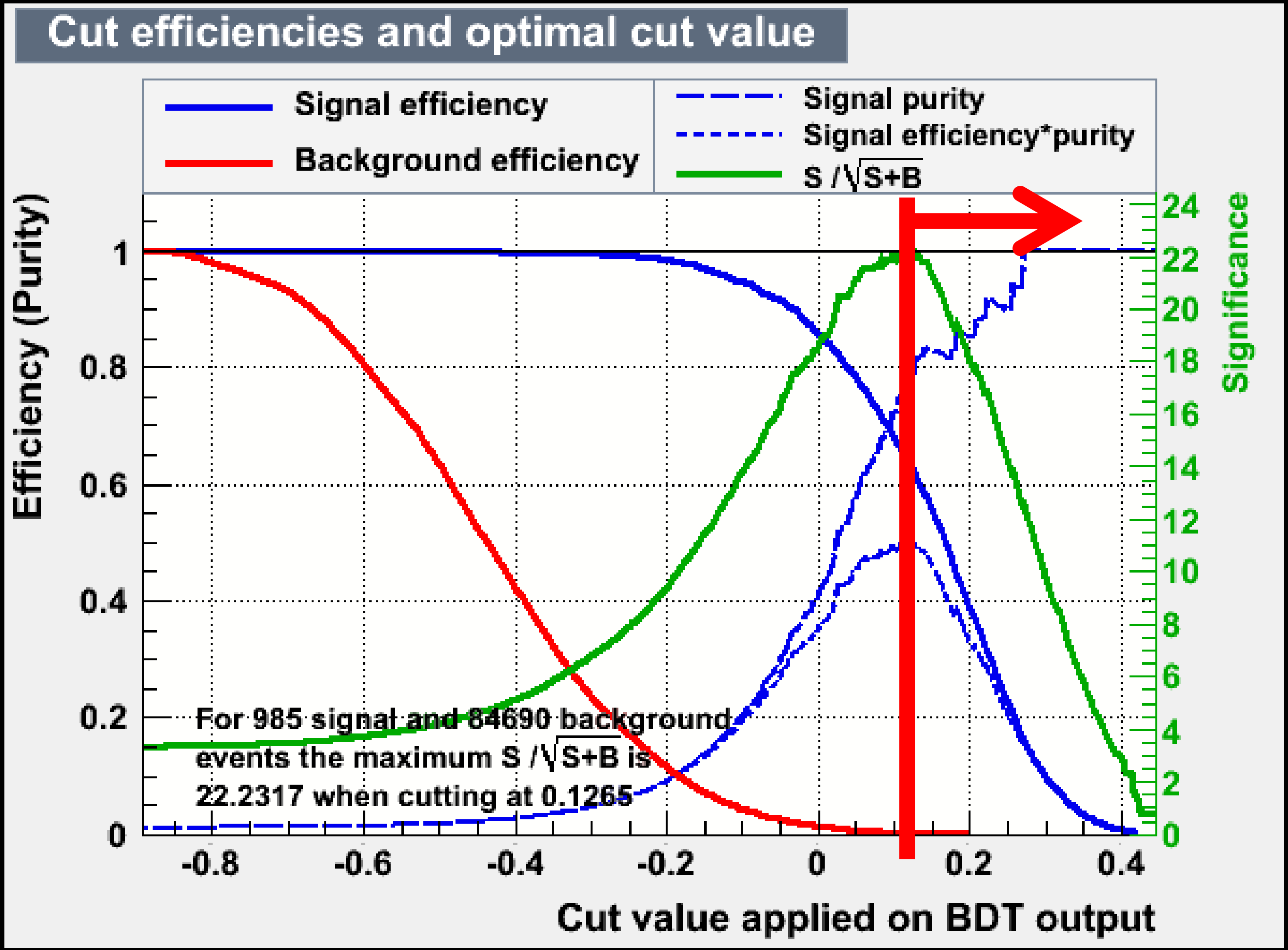
M_{col}= tau pair mass w/ collinear approximation

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

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

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% Cut-based Extrapolation from M_h = 120 GeV	5.0% Cut-based	4.5% TMVA	7.4% Cut-based	6.0% TMVA

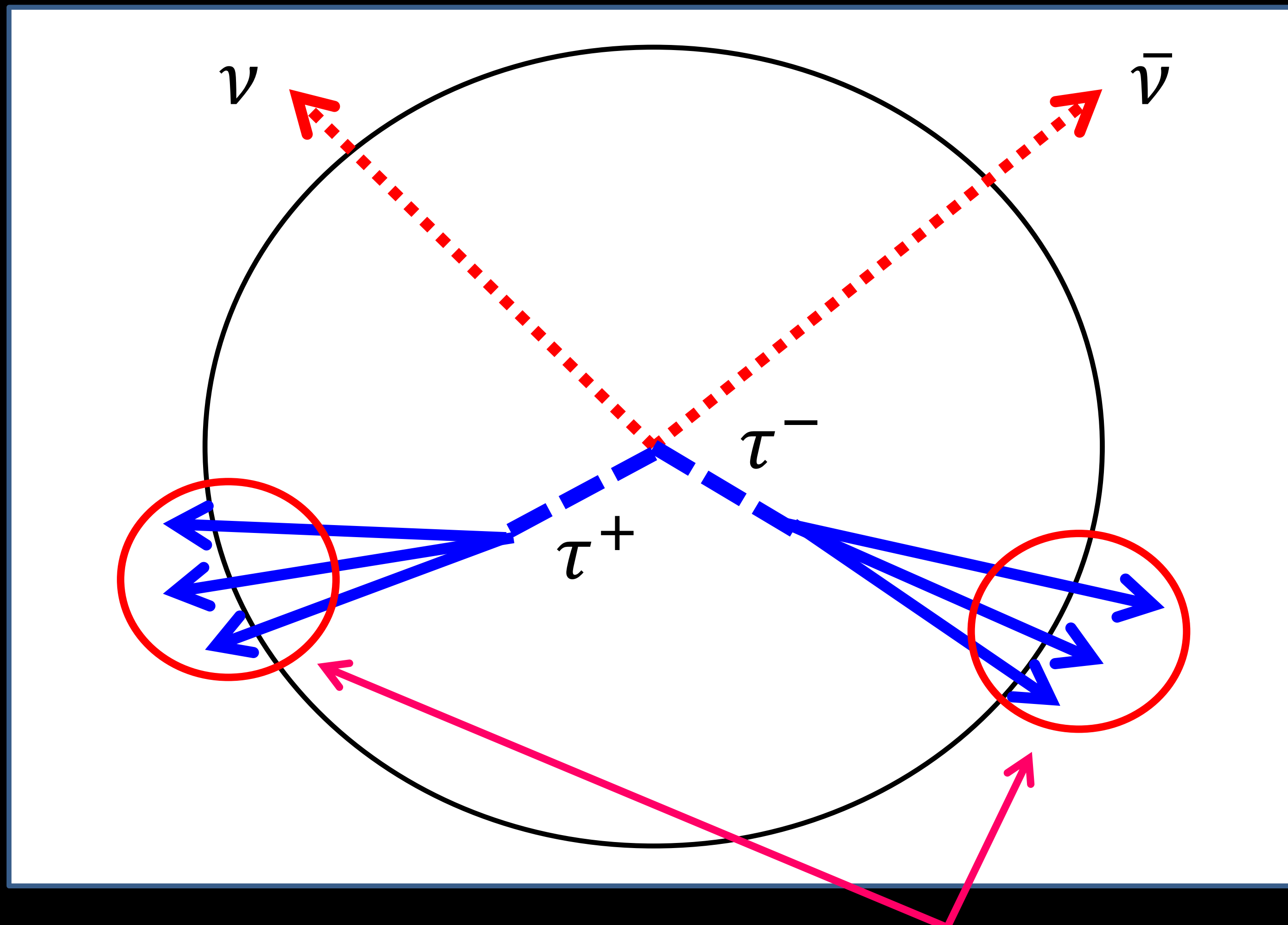
Future Plans

- 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



$m_{\text{cluster}} < 2$ GeV

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

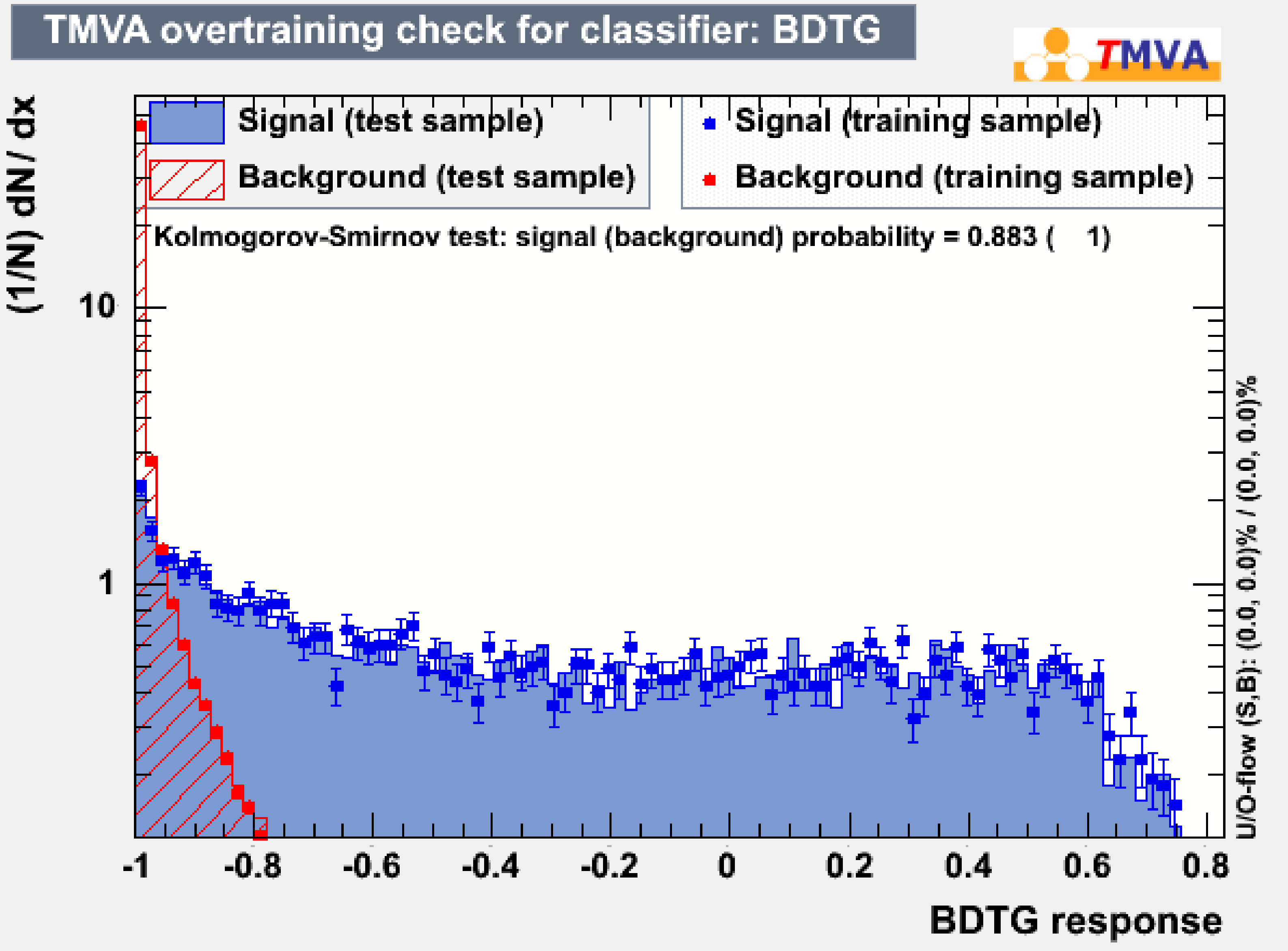
	$\nu\nu h$ $h\to\tau\tau$	$\nu\nu h$ $h\nrightarrow\tau\tau$	2f	4f $\nu\nu\tau\tau$	4f $\nu\nu\ell\ell$	4f $\nu\nu\tau\ell$	4f others	5f	6f	aa_4f	qqh llh	signi.
No Cut	5401	7.954e04	1.319e07	1.452e05	9.450e05	6.309e05	1.426e07	6.985e04	5.888e05	1.041e05	4.372e04	0.985
pre-sel	4676	6062	3.973e06	1.070e05	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_{vis}	4263	2438	8.235e05	5.660e04	2.064e05	1.492e05	7.964e05	7244	2775	2.476e04	262.9	2.96
E_{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
$d_0$sig	1672	71.14	652.1	7096	1366	4848	1905	155.0	135.1	241.0	11.41	12.4
$z_0$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_{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

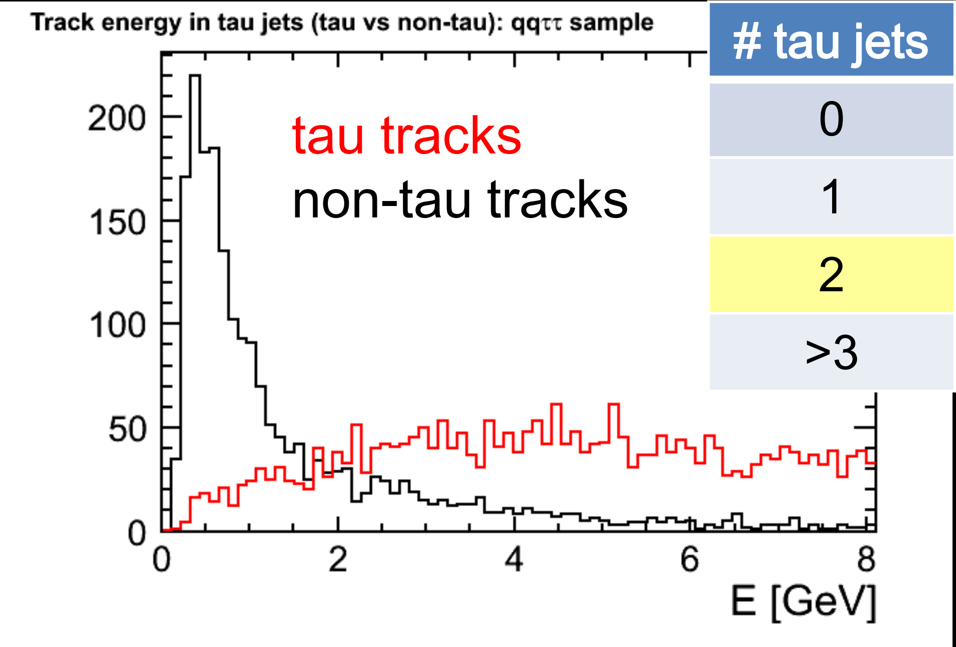
1. Order charged tracks by largest energy
2. Select the first track
3. Combine neighboring particles -> “Tau Jet”
   - Combined mass < 2 GeV && cosθ w.r.t. jet axis > 0.98
4. Tau selection (tuned for rejecting qq background)
   1. Tau Jet energy > 3 GeV
   2. Veto >=3 prong + neutrals (> 1 GeV)
   3.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

ZZ -> qq$\tau\tau$ 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	$qq\tau\tau$	$qql\nu$
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)

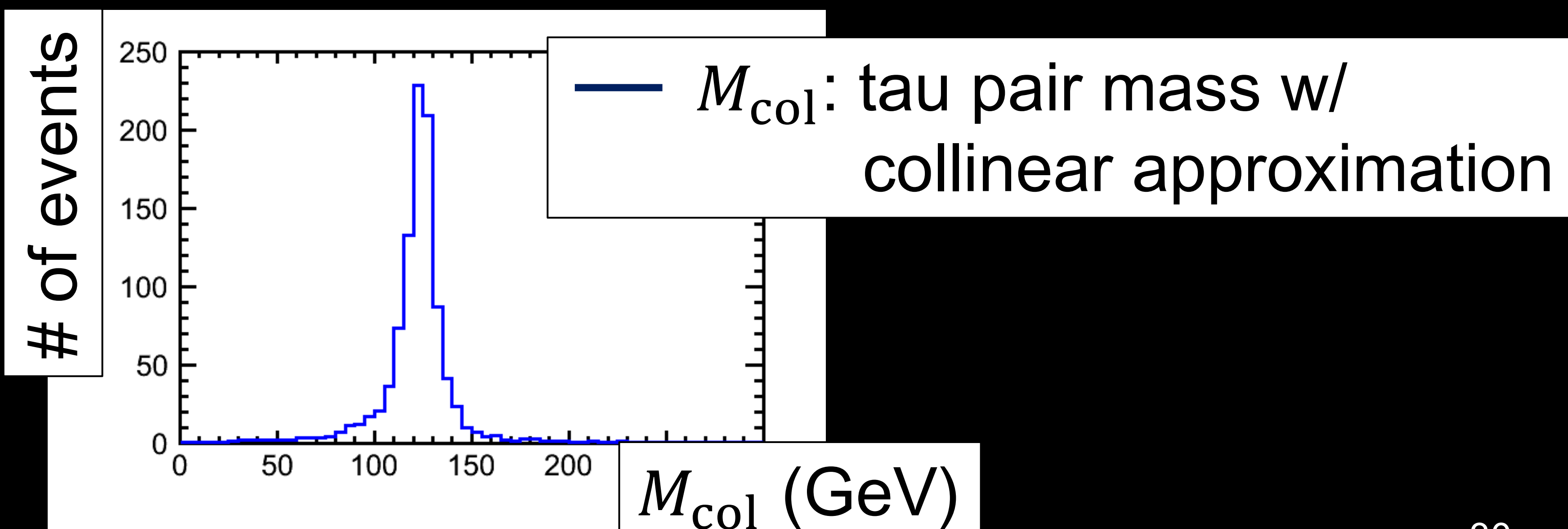
Collinear Approximation

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: $E_{\text{vis}} < 475$
Cut 3: $P_t > 165$
Cut 4: thrust < 0.93
Cut 5: $|\cos\theta_{\text{miss}}| < 0.92$
Cut 6: $55 < M_Z(M_{q\bar{q}}) < 145$
Cut 7: $E_Z(E_{q\bar{q}}) > 180$
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: $\cos\theta_{\text{acop}} < 0.91$
Cut 12: $\log_{10}|d_0\text{sig}(\tau^+)| + \log_{10}|d_0\text{sig}(\tau^-)| > 0$
Cut 13: $110 < M_{\text{col}} < 140$
Cut 14: $195 < E_{\text{col}} < 290$
Cut 15: $M_{\text{recoil}} > 50$

	$\nu\nu h$ $h \to \tau\tau$	$\nu\nu h$ $h \nrightarrow \tau\tau$	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_{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
$\cos\theta_{\text{miss}}$	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
$\cos\theta_{\text{acop}}$	712.2	89.80	160.7	5254	199.1	1452	64.33	355.9	7.82
$d_0\text{sig}$	683.9	48.26	153.6	3121	89.09	773.8	35.69	238.2	9.54
M_{col}	584.1	7.020	7.189	237.6	4.800	54.89	1.975	34.22	19.1
E_{col}	572.1	5.850	7.189	181.0	3.082	32.27	0	32.82	19.8
M_{recoil}	560.7	5.850	7.189	155.8	3.082	32.27	0	31.66	19.9

TMVA Analysis: Inputs

of tracks, M_{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_{col}, E_{col}, M_{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