Measuring BR($h \to \tau^+\tau^-$) at the ILC: a full simulation study

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Introduction

Higgs boson found

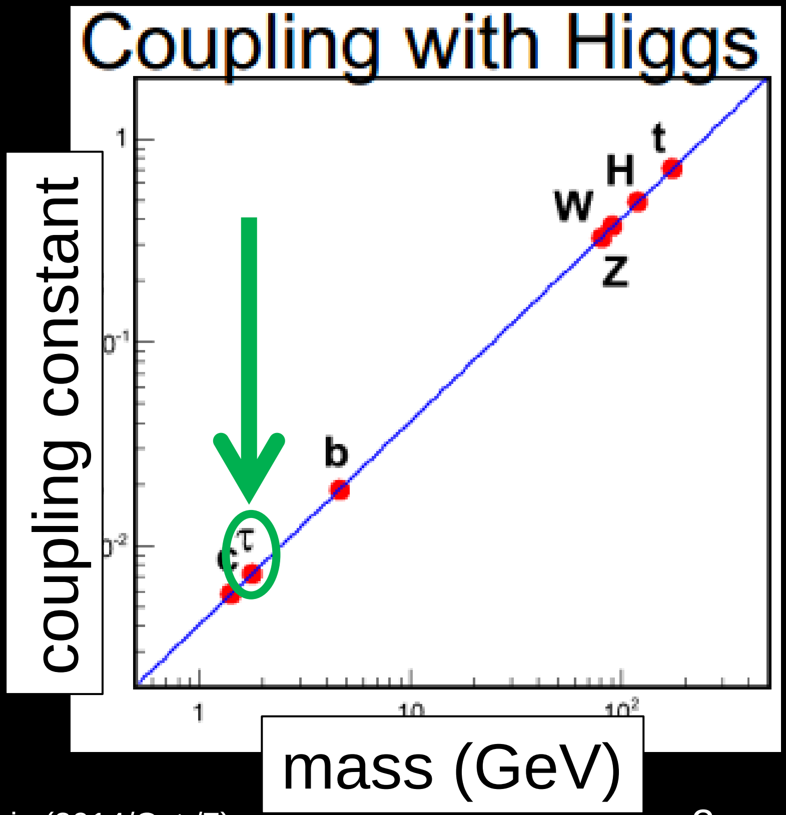
Next step: understanding details of new particle through the precise measurement

Branching Ratio (BR)

$$(h \rightarrow \tau^{+}\tau^{-})$$

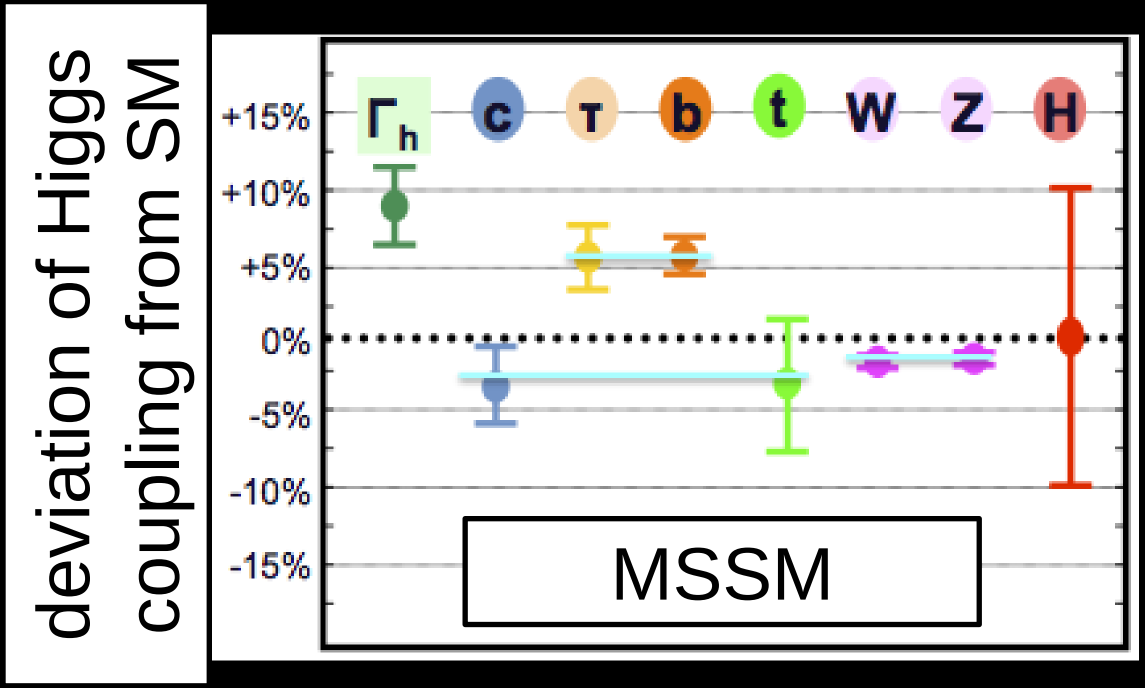
- understanding basic property
- probe for the new physics

O(%) accuracy is needed



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 $BR(h \to \tau^+\tau^-)$ an ideal probe for new physics.

Purpose of This Study

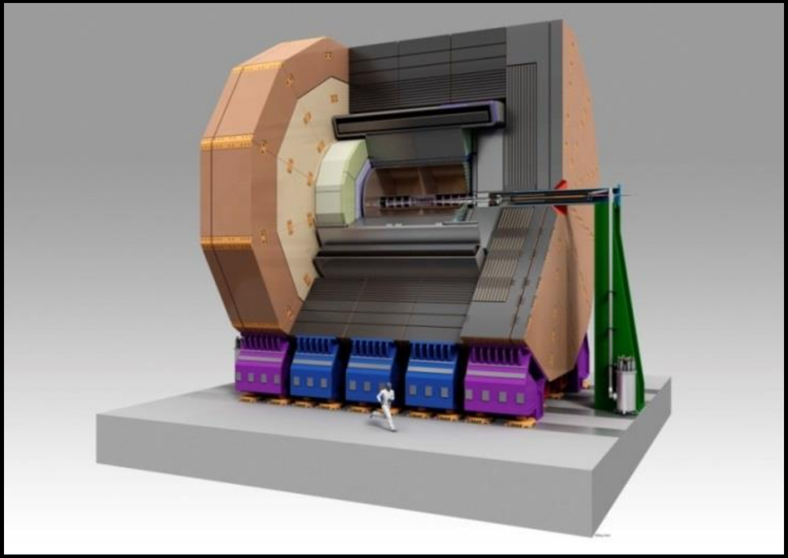
Estimating the precision of BR$(h \to \tau^+\tau^-)$ at the ILC with ILD detector

We estimated the precision with **full detector simulation** (ILD) at the center-of-mass energy of 250 GeV and 500 GeV.

↓ ECFA2013 LoI sample (M_h = 120 GeV)

↓ LCWS2013 TDR sample (M_h = 125 GeV)

ILD detector model



Today's Talk: 250 GeV Analysis

Higgs properties

- **M_h = 125 GeV**
- BR($h \to \tau^+\tau^-$) = 6.32% (LHC Higgs XS WG)

Machine parameters

- Center-of-mass energy = 250 GeV
- Integrated luminosity = 250 fb^{-1}
- Beam polarization: $(e^-, e^+) = (-0.8, +0.3)$

Simulation Settings

- ILD full detector simulation (ILD_o1_05)
- TDR sample (higgs_ffh, 2f, 4f, 1f_3f, aa_2f)
  + new $h \to \tau^+\tau^-$ sample (next page)

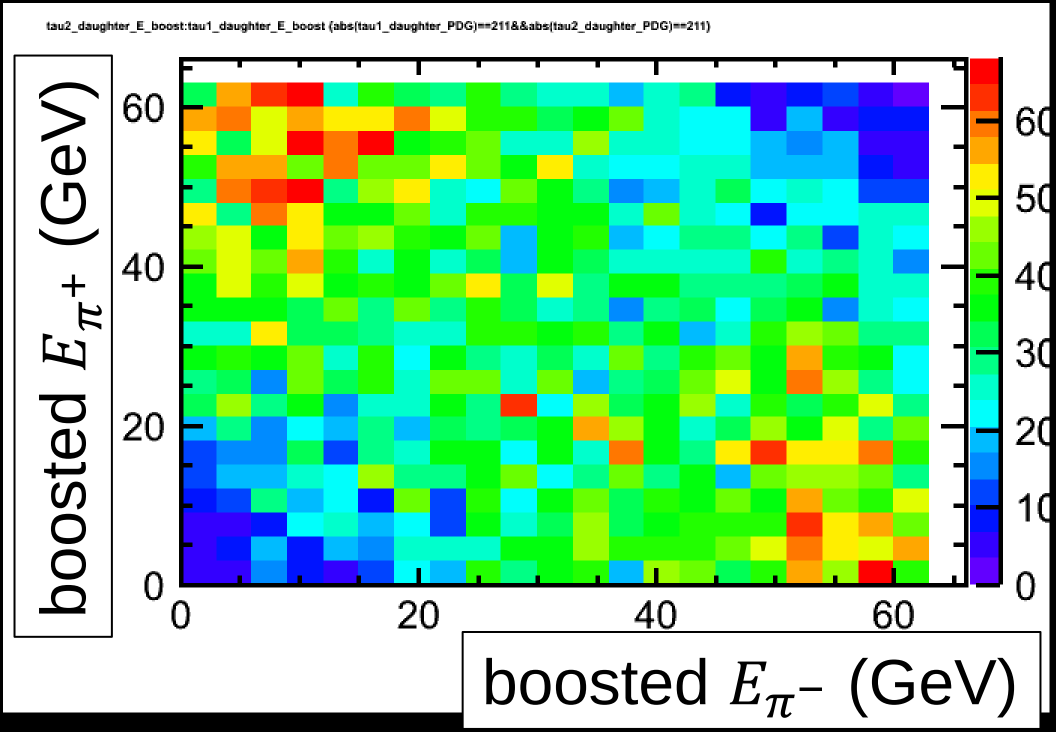
Tau Polarization

Tau polarization in $h \to \tau^+\tau^-$ decay of TDR sample was not treated properly.
$(h \to \tau^+(s\uparrow)\tau^-(s\downarrow)$ or $\tau^+(s\downarrow)\tau^-(s\uparrow))$

⇩

developed new event generator which fixed this problem
(by H. Yokoyama)

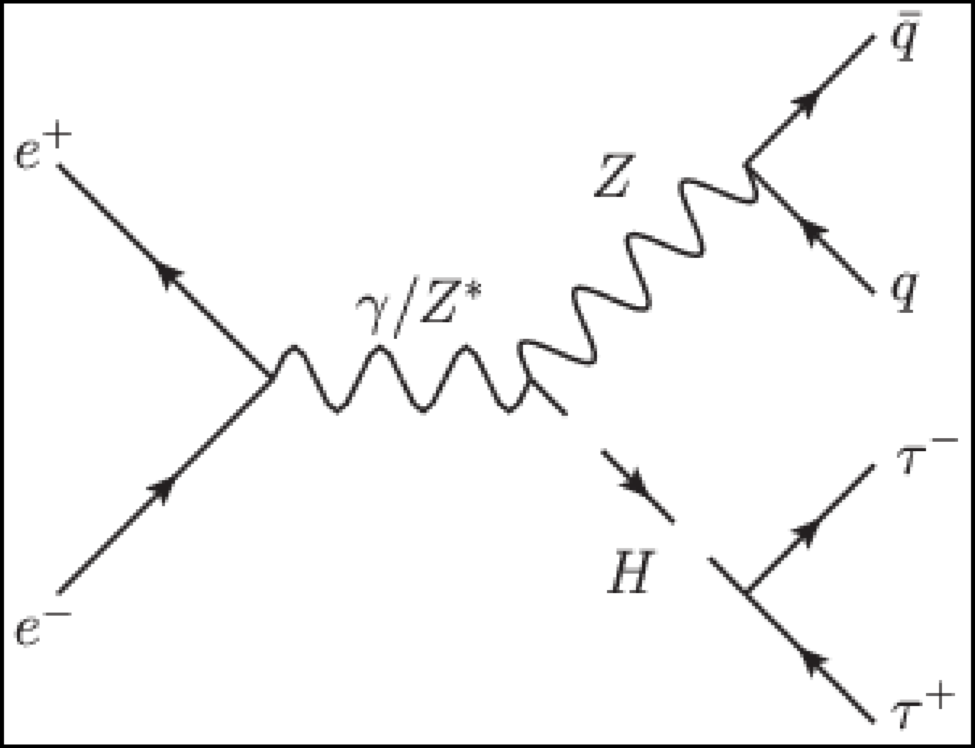
We generated new samples and analyzed.



Signal and Background

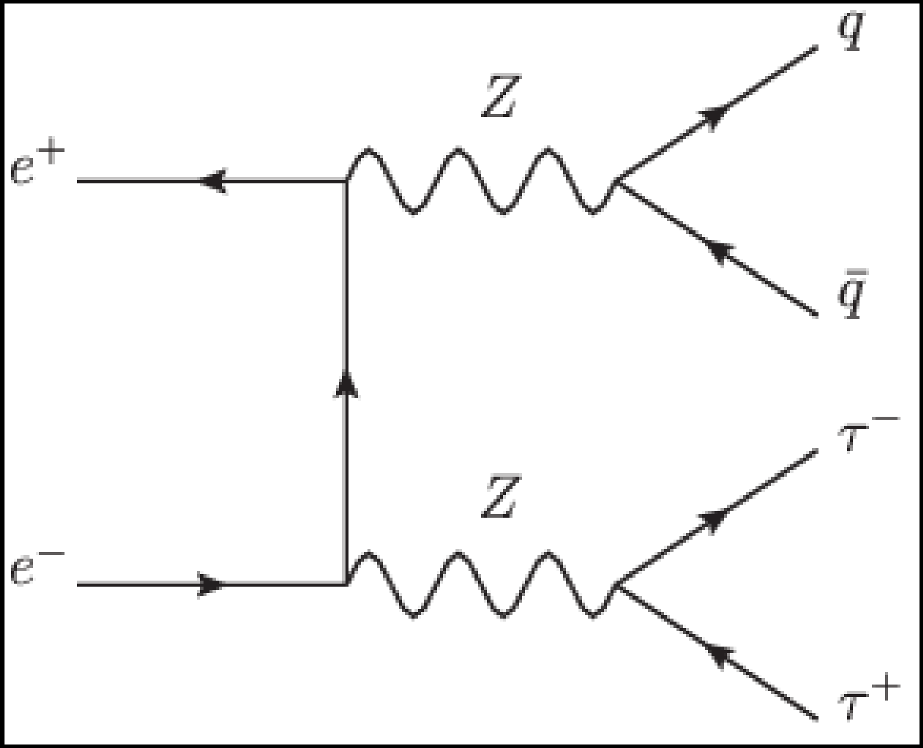
Signal

$$e^+e^- \rightarrow Zh \rightarrow (q\bar{q})(\tau^+\tau^-)$$

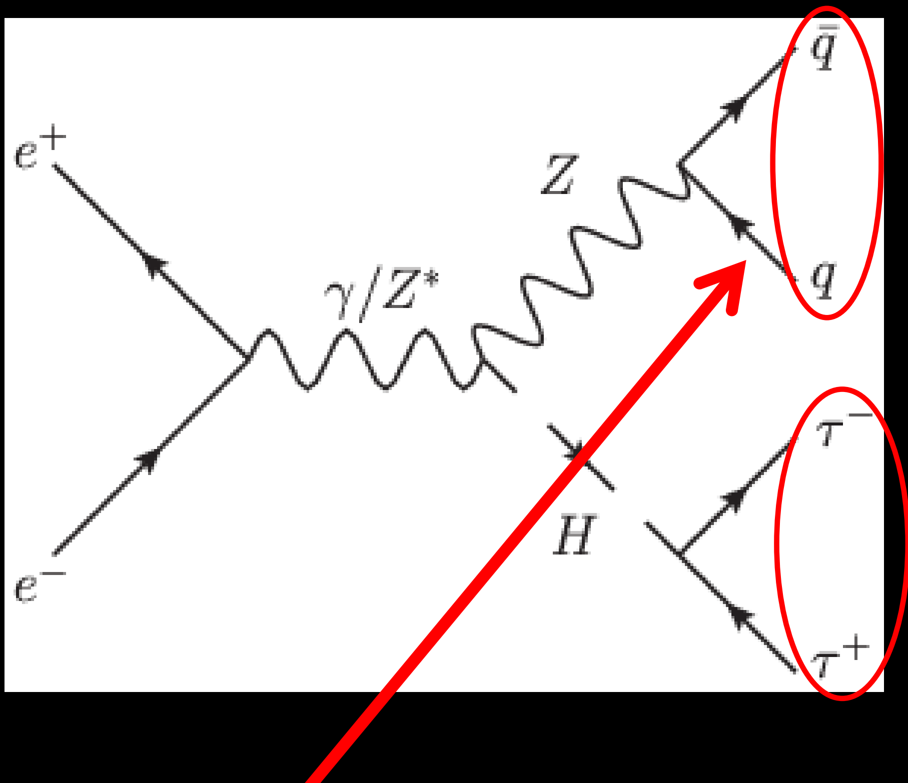


Main background

$$e^+e^- \rightarrow ZZ \rightarrow (q\bar{q})(\tau^+\tau^-)$$



Event Reconstruction



(1) **Tau reconstruction**

- Tau jet finder

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

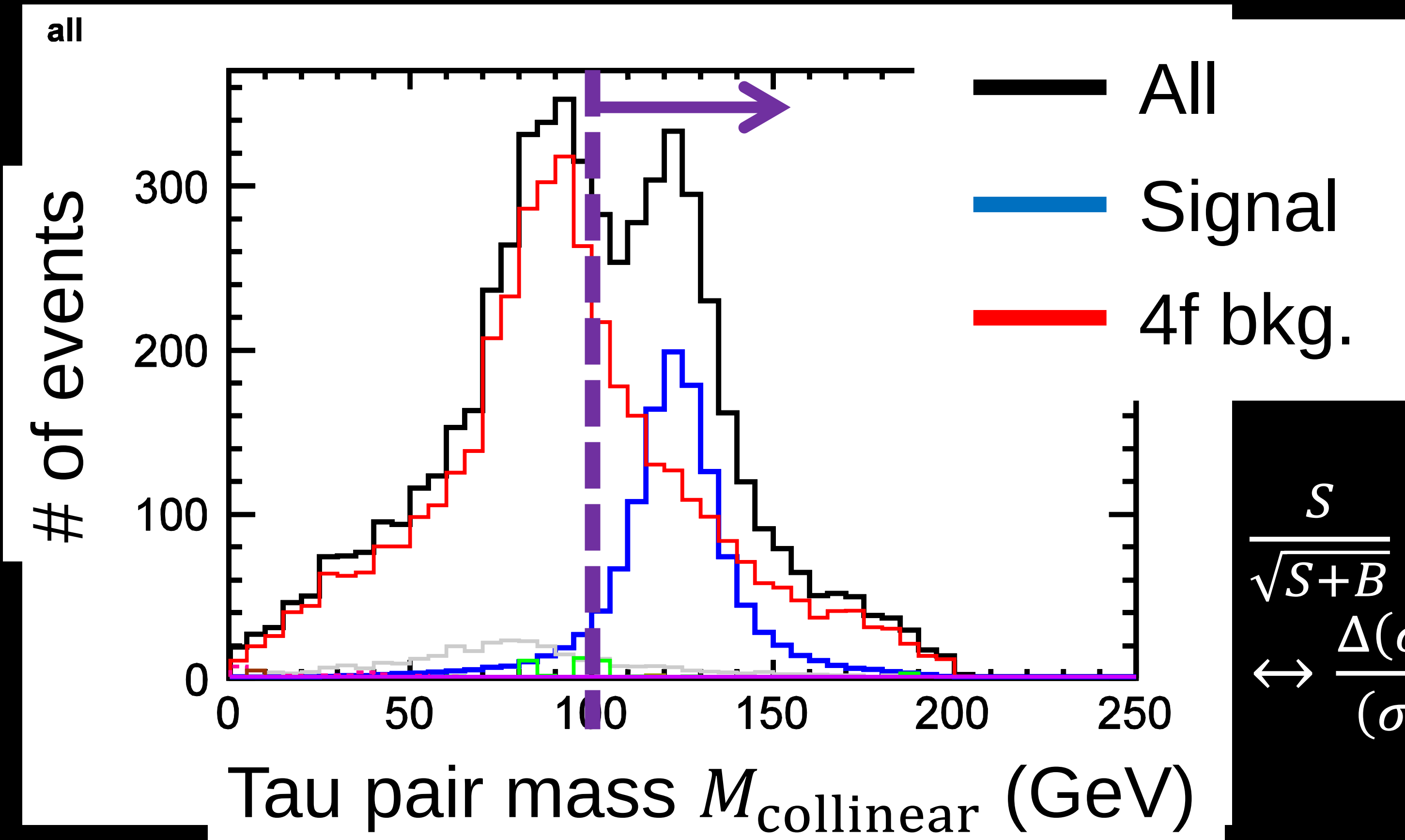
- Collinear approximation

tau pair mass reconstruction

(2) **Z reconstruction**

Durham algorithm into 2-jets

Cut-based Analysis



250 GeV
250 fb^{-1}

$$\frac{S}{\sqrt{S+B}} = 25.5\sigma$$

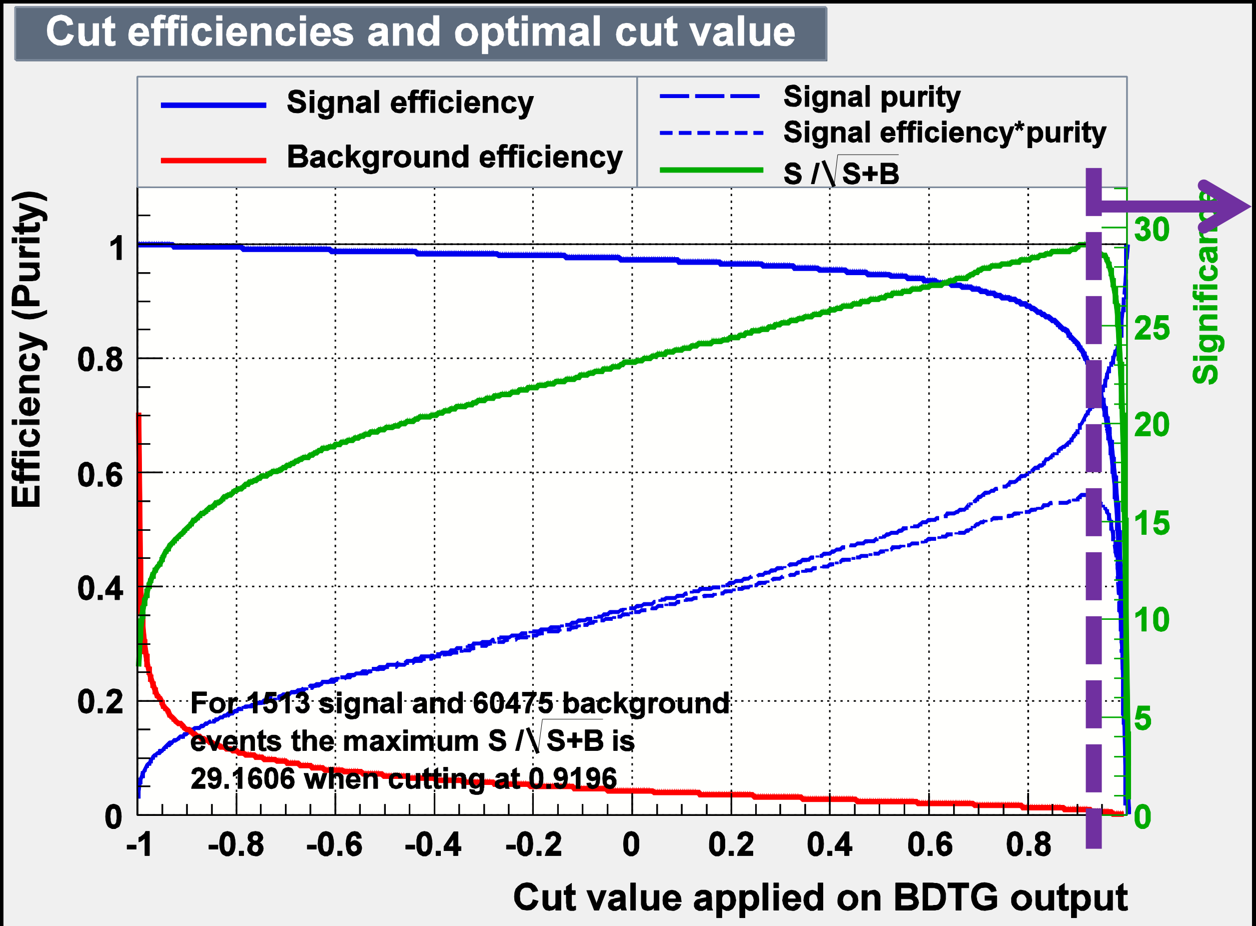
$$\leftrightarrow \frac{\Delta(\sigma\times\mathrm{BR})}{(\sigma\times\mathrm{BR})} = \mathbf{3.9\%}$$

	signal	4f	other SM bkg.
No cut	3318	$1.021*10^7$	$4.226*10^8$
After	**1002**	498.5	38.34

Analysis Using TMVA

We used **Boosted Decision Tree** technique.

(BDT and BDTG, training parameters are optimized.)



Remained events

$N_{sig} = 1202$

$N_{bkg} = 497.5$

$$\frac{S}{\sqrt{S+B}} = 29.1\sigma$$

$$\leftrightarrow \frac{\Delta(\sigma\times\mathrm{BR})}{(\sigma\times\mathrm{BR})} = \mathbf{3.4\%}$$

~15% improved from cut-based!

Comparison with M_h = 120 GeV Results

250 GeV 250 fb^{-1}	Extrapolation from M_h = 120 GeV	M_h = 125 GeV
$\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$	**4.2%** $q\bar{q}h + \ell^+\ell^- h$ (ref: LC-REP-2013-001)	**3.4%** $q\bar{q}h$ only
Conditions	- cut-based only - tau finder was not so optimized	- using multivariate technique - optimized tau finder

Summary

- We prepared new signal sample which including proper tau polarization, and analyzed 250 GeV $q\bar{q}h$ mode.
- Boosted Decision Tree technique is very useful, and we can archive 3% level precision of $(\sigma \times \mathrm{BR})$ even only using 250 GeV $q\bar{q}h$.
- Plan: finalize this analysis for all modes at 250 GeV and 500 GeV

BACKUPS

Current Numbers

250 GeV 250 fb^{-1}	$q\bar{q}h$	$\nu\bar{\nu}h$	e^+e^-h	$\mu^+\mu^-h$
$\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$	**3.4%**	46.0%	16.1%	14.7%

Today's talk

Extrapolation from M_h = 120 GeV
Cut-based only
will be analyzed with new sample

500 GeV 500 fb^{-1}	$q\bar{q}h$	$\nu\bar{\nu}h$	e^+e^-h	$\mu^+\mu^-h$
$\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$	4.7%	6.8%	31.2%	17.6%

will be re-analyzed with new sample

by T. Suehara

TaJet Finder (1)

High-purity tau tagging in presence of jet background

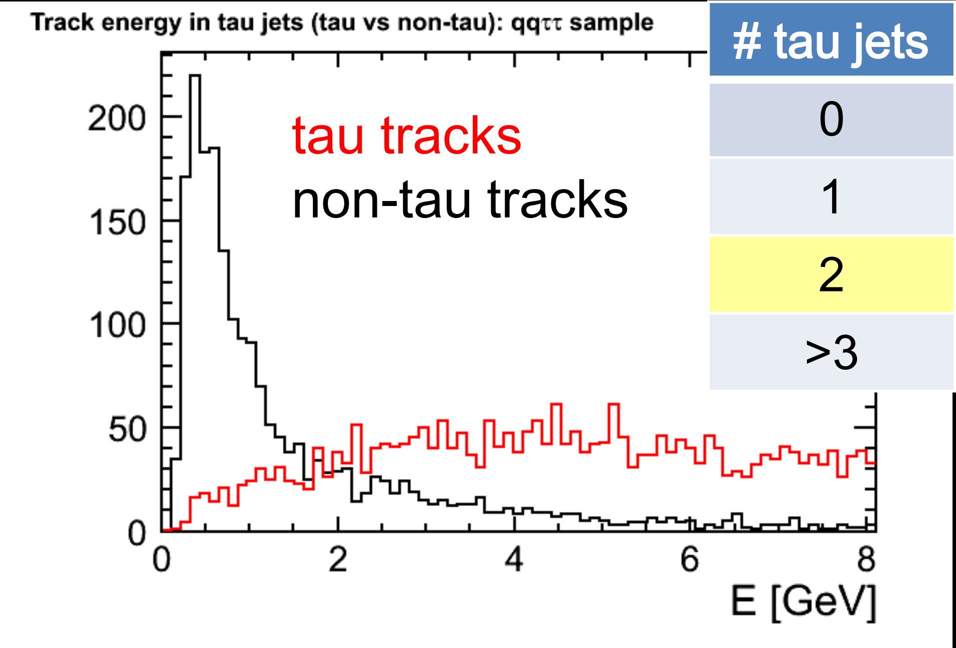
1. Order charged tracks by largest energy
2. Select the first track
3. Combine neighboring particles -> "Tau Jet"
   - Combined mass < 2 GeV && $\cos\theta$ w.r.t. jet axis > 0.99
4. Tau selection (tuned for rejecting qq background)
   1. Tau Jet energy > 3 GeV
   2. Veto >=3 prong + neutrals (> 1 GeV)
   3. Cone energy ($E_{cone} < 0.1E_{taujet}$) with $\cos\theta_{cone} = 0.95$

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_H)

Assumptions :

- visible τ decay products and νs are collinear
- contribution of missing momentum comes only from νs of τ decay

Collinear Approximation

$\tau_{1\mathrm{vis}} \equiv (E_{\mathrm{vis1}}, \boldsymbol{p}_{\mathrm{vis1}}), \tau_{2\mathrm{vis}} \equiv (E_{\mathrm{vis2}}, \boldsymbol{p}_{\mathrm{vis2}})$ ← visible product(s) from tau

$\tau_{1\mathrm{inv}} = a(|\boldsymbol{p}_{\mathrm{vis1}}|, \boldsymbol{p}_{\mathrm{vis1}}), \tau_{2\mathrm{inv}} = b(|\boldsymbol{p}_{\mathrm{vis2}}|, \boldsymbol{p}_{\mathrm{vis2}})$ ← neutrino(s) from tau

$$\begin{cases} a = \dfrac{p_{\mathrm{mis}_y} p_{\tau 2\mathrm{vis}_x} - p_{\mathrm{mis}_x} p_{\tau 2\mathrm{vis}_y}}{p_{\tau 1_y} p_{\tau 2_x} - p_{\tau 1_x} p_{\tau 2_y}} \\ b = \dfrac{p_{\mathrm{mis}_y} p_{\tau 1\mathrm{vis}_x} - p_{\mathrm{mis}_x} p_{\tau 1\mathrm{vis}_y}}{p_{\tau 1_x} p_{\tau 2_y} - p_{\tau 2_x} p_{\tau 1_y}} \end{cases}$$

Cut-based Analysis

Cut 0 (pre-cuts): # of q jets = 2, # of $\tau^{+}(\tau^{-})$ = 1,
# of tracks >= 9, $M_{\mathrm{col}} > 0$, $E_{\mathrm{col}} > 0$

Cut 0.5 (basic cuts): $90 < E_{\mathrm{vis}} < 285$, $75 < M_{\mathrm{vis}} < 275$, $P_t > 40$,
thrust < 0.97, $|\cos\theta_{\mathrm{miss}}| < 0.99$

Cut 1: $M_{\mathrm{vis}} < 240$

Cut 2: $|\cos\theta_{\mathrm{miss}}| < 0.98$

Cut 3: $E_Z(E_{qq}) < 125$

Cut 4: $M_Z(M_{qq}) > 80$

Cut 5: $E_{\tau\tau} < 130$

Cut 6: $M_{\tau\tau} < 115$

Cut 7: $\cos\theta_{\tau\tau} < -0.54$

Cut 8: $E_{\mathrm{col}} < 210$

Cut 9: $M_{\mathrm{col}} > 100$

Cut 10: $\log_{10}|d_0\mathrm{sig}(\tau^{+})| + \log_{10}|d_0\mathrm{sig}(\tau^{-})| > -0.2$

Cut 11: $\log_{10}|z_0\mathrm{sig}(\tau^{+})| + \log_{10}|z_0\mathrm{sig}(\tau^{-})| > -0.4$

Cut 12: $M_{\mathrm{recoil}} > 115$

pre-cuts:
require signal topology
basic cuts:
suppress trivial bkg. events

Cut Table (AeX = A*10^X)

表 1　250 GeV $q\bar{q}h$ Cut-based 解析の cut table。eX は $\times 10^X$ を表す。

	$q\bar{q}h$ $h \to \tau\tau$	$q\bar{q}h$ $h \not\to \tau\tau$	$\nu\bar{\nu}h$ $\ell\ell h$	2f	4f	1f_3f	aa_2f	sig.
None	3318	4.920e4	2.712e4	2.863e7	1.021e7	2.305e8	1.634e8	0.160
pre-sel	1529	671.4	3847	5.877e4	2.522e5	5.195e4	1.617e5	2.10
basic	1513	646.9	3679	1.865e4	2.314e5	2434	79.40	2.98
E_{vis}	1493	478.8	1879	5004	1.642e5	1531	69.41	3.57
θ_{miss}	1479	465.1	1827	4294	1.586e5	1069	41.97	3.61
E_Z	1421	233.2	776.9	2546	1.403e5	873.8	40.97	3.72
M_Z	1282	203.4	668.8	200.3	1.611e4	102.7	4.997	9.41
$E_{\tau\tau}$	1279	203.3	668.3	179.1	1.571e4	101.7	4.997	9.50
$M_{\tau\tau}$	1274	203.1	664.5	179.1	1.559e4	101.6	4.997	9.49
$\theta_{\tau\tau}$	1262	35.73	335.0	53.17	5291	38.09	4.997	15.1
E_{col}	1220	22.58	306.3	44.05	4134	32.29	4.997	16.1
M_{col}	1106	11.52	78.79	17.26	1564	4.000	0	21.0
$d_0$sig	1065	7.422	49.13	17.26	1132	4.000	0	22.3
$z_0$sig	1038	4.576	35.15	17.26	915.9	3.100	0	23.1
M_{recoil}	1002	3.553	27.52	4.818	498.5	2.450	0	25.5

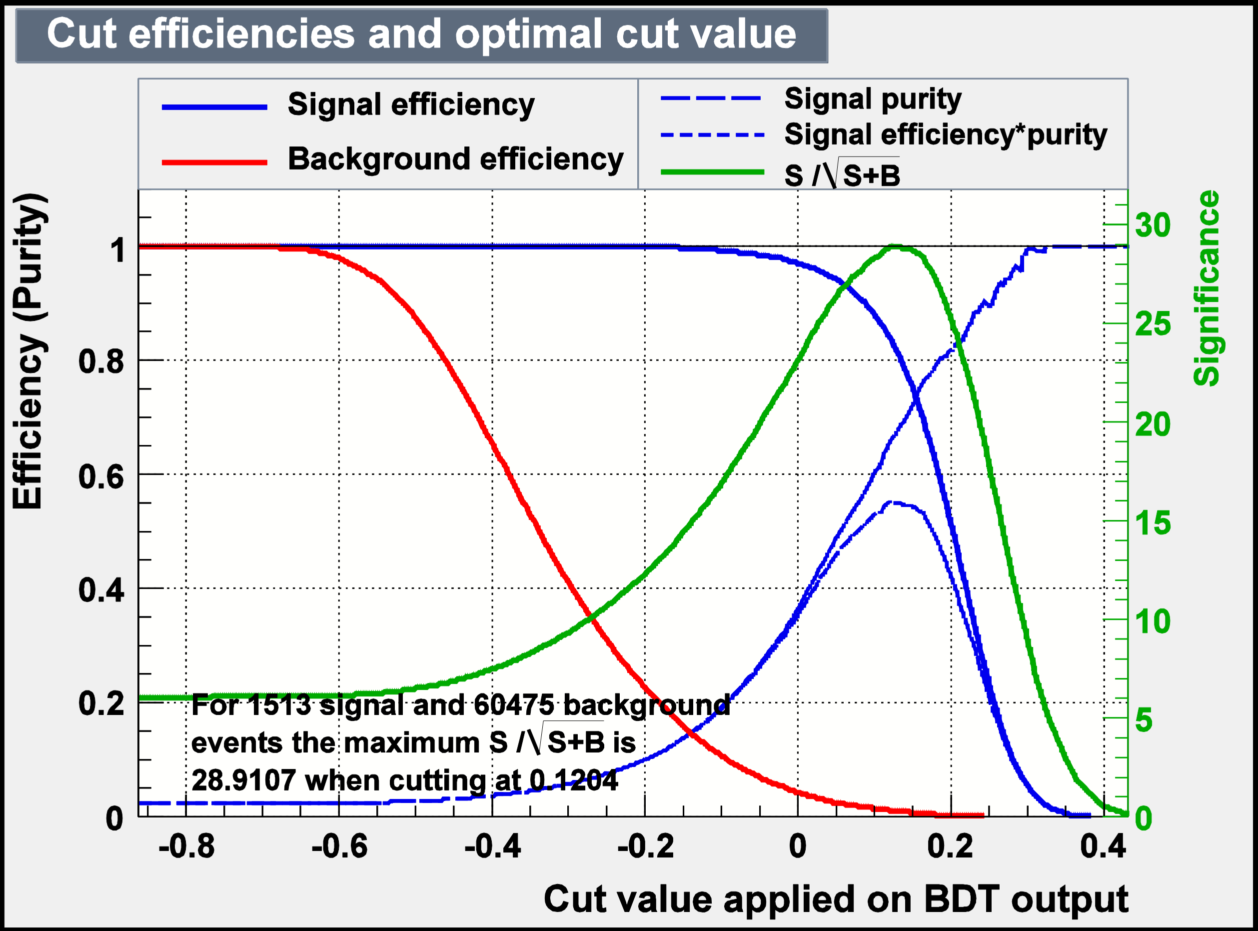
TMVA Analysis (1)

- Use samples which already applied pre-cuts and basic cuts
- Additional cuts are also applied to suppress trivial process: $60 < E_Z < 180$, $35 < M_Z < 160$, $E_{\tau\tau} < 140$, $M_{\tau\tau} < 125$, $\cos\theta_{\tau\tau} < -0.4$
- Use BDT and BDTG method

TMVA Analysis (2)

- BDT parameters:
  - MaxDepth = 4, NTrees = 900
- BDTG parameters:
  - Shrinkage = 0.30, MaxDepth = 6, NTrees = 1200

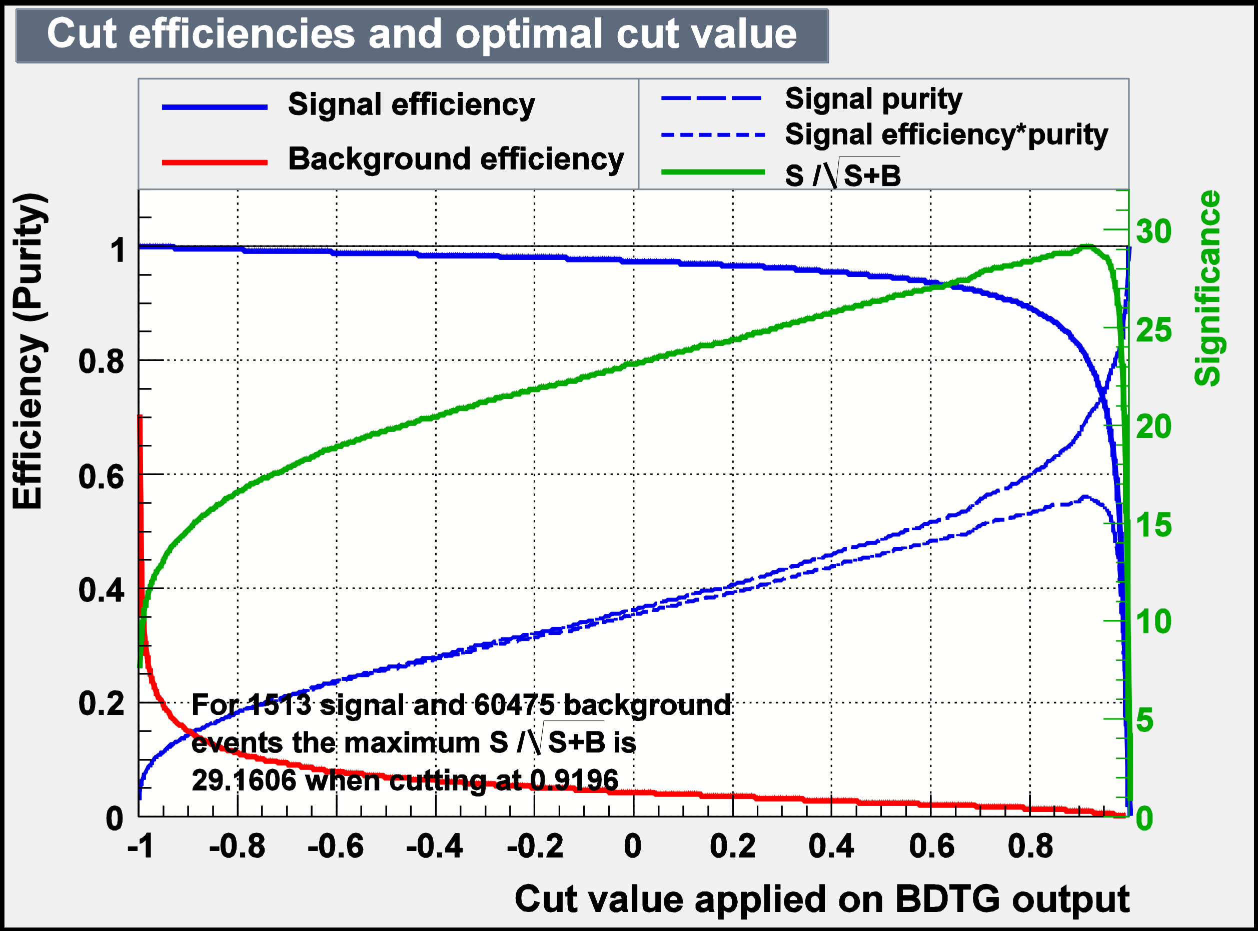
BDT Result



$$\frac{S}{\sqrt{S+B}} = 28.9\sigma$$

$$\leftrightarrow \frac{\Delta(\sigma\times\mathrm{BR})}{(\sigma\times\mathrm{BR})} = \mathbf{3.5\%}$$

BDTG Result



$$\frac{S}{\sqrt{S+B}} = 29.1\sigma$$

$$\leftrightarrow \frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})} = \mathbf{3.4\%}$$