

Study of Direct top Yukawa Coupling Measurement at ILC with $\sqrt{s} = 500$ GeV

LCWS 2014 6-10 Oct. 2014 @ Belgrade

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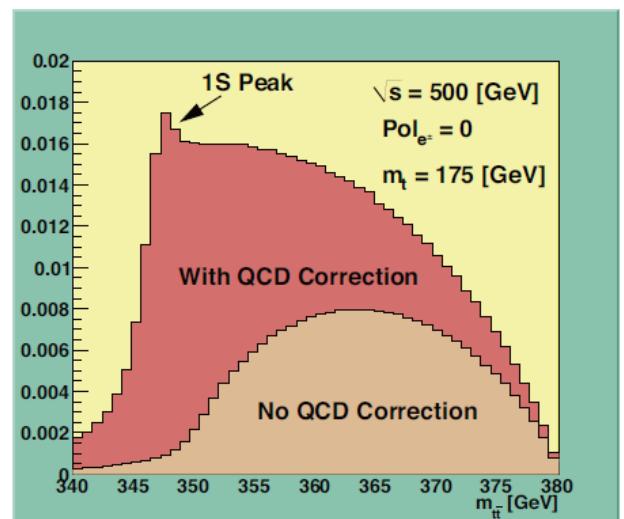
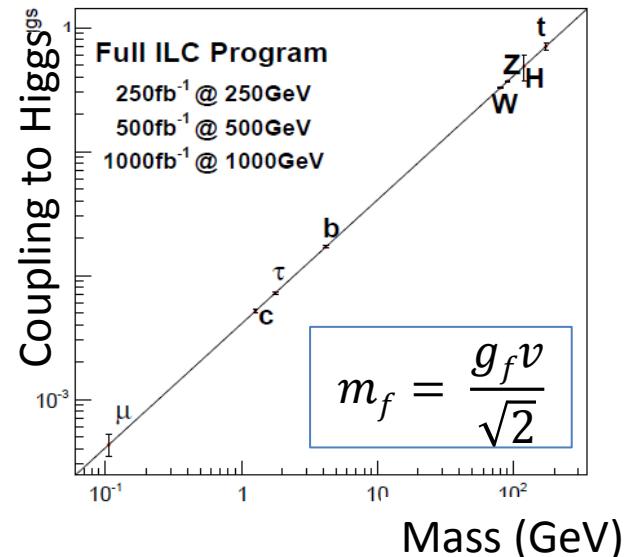
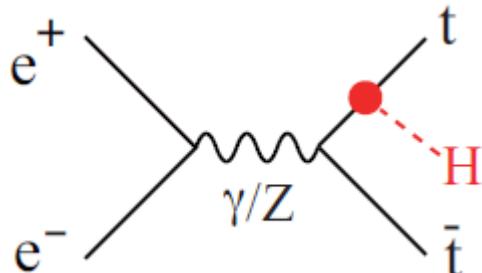
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Introduction

- We are working on ttH study assuming
 - $M_H=125$ GeV.
 - Polarization : $(Pe^-, Pe^+) = (-0.8, +0.3)$
 - Integrated luminosity 500 fb^{-1}
 - ILD full simulation
- ttbar cross section is increased around ttbar threshold by ttbar bound-state effect
- ttH cross section is enhanced
- ttZ cross section is also increased

We can directly measure the top-Yukawa coupling via ttH channel at $\sqrt{s} = 500$ GeV.



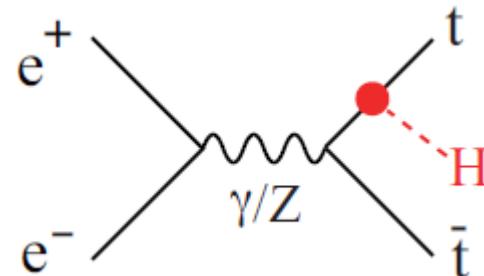
Signal and Background

Signals

- $t\bar{t}h \rightarrow 8\text{jets}$ ($h \rightarrow bb$)
- $t\bar{t}h \rightarrow l\nu + 6\text{jets}$ ($h \rightarrow bb$)

Backgrounds

- $t\bar{t}Z$, $t\bar{t}g$ ($g \rightarrow bb$), $t\bar{t}W$



Software tools

- analysis framework : LCIO/Marlin
- event generation : whizard & physsim
- detector simulation : Mokka/Geant4
- Particle Flow Algorithm : PandoraPFA

Expected # of events @ 500fb⁻¹

- $\sqrt{s} = 500 \text{ GeV}$, $M_h = 125 \text{ GeV}$, $(Pe^-, Pe^+) = (-0.8, +0.3)$
- production cross section
- Branching ratio

Process	$\sigma (\text{fb})$
$e^-e^+ \rightarrow tth$	0.485
$e^-e^+ \rightarrow ttZ$	1.974
$e^-e^+ \rightarrow ttg(bb)$	1.058
$e^-e^+ \rightarrow tbW$	979.8

Decay mode	Branching ratio
$h \rightarrow bb$	0.577
$tt \rightarrow bqqbqq$	0.457
$tt \rightarrow blvbqq$	0.438
$tt \rightarrow blvblv$	0.105

- expected # of signals and Backgrounds(@500fb⁻¹)

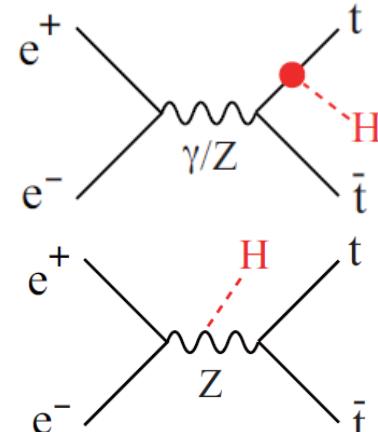
tth(tt6j, hbb)	63.9	tth(ttlN4j,hbb)	61.3
tth(ttall, hnobb)	102.6	ttZ	987
tth(ttlvlv2j, hbb)	14.6	ttg(bb)	529
		tbW	489902

$t\bar{t} \rightarrow 8\text{jets}(\text{l}\nu+6\text{jets})$ analysis

- interference term is negligible
- counting analysis with cut based event selection

In this analysis, higgs decays into two b jets

- **4 b jets** out of 8(6) jets (b tagging: LCFIPlus)
- **No (one) isolated lepton**
- Use Kt clustering only for removing low Pt background



Event Selection

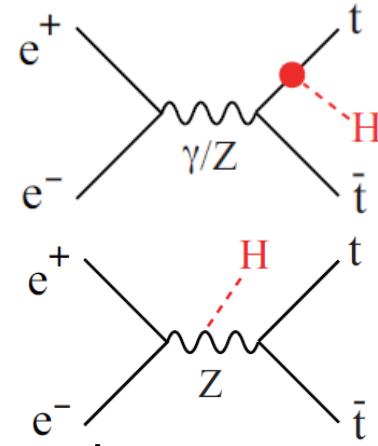
- signal topology
 - ✓ $\chi^2 \leq 11.2$ (16.5)
 - ✓ $| \text{Jet } \cos\theta | \leq 0.99$
 - ✓ jet pairing
- detector acceptance
- kinematics
 - ✓ Leading 2 Jet Energy Sum
 - ✓ Lowest 3 Jet Energy Sum (for 8jets mode)
(Lowest 2 Jet Energy Sum (for 6jets mode))
 - ✓ Missing momentum $> 20 \text{ GeV}$ (for 6jtes mode)
 - ✓ reconstructed mass
 - ✓ top candidate $M_{jjj} \geq 140 \text{ GeV}$
 - ✓ higgs candidate $M_{jj} \geq 80 \text{ GeV}$
 - ✓ $90 \text{ GeV} \leq h \text{ candidate } M_{jj} \leq 155 \text{ GeV}$

$t\bar{t} \rightarrow 8\text{jets}(\text{l}\nu+6\text{jets})$ analysis

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Event Selection

- **signal topology**
 - ✓ χ^2 cut (6, 8 jet event)
 - ✓ No(one Isolated Lepton)
 - ✓ B jet candidate ≥ 4
- **detector acceptance**
 $|{\text{Jet}} \cos\theta| \leq 0.99$
- **jet pairing**
 $\chi^2 \leq 11.2$ (16.5)
- **kinematics**
 - ✓ Leading 2 Jet Energy Sum
 - ✓ Lowest 3 Jet Energy Sum (for 8jets mode)
(Lowest 2 Jet Energy Sum (for 6jets mode))
 - ✓ Missing momentum > 20 GeV (for 6jtes mode)
- **reconstructed mass**
 - ✓ top candidate $M_{jjj} \geq 140$ GeV
 - ✓ higgs candidate $M_{jj} \geq 80$ GeV
 - ✓ $90\text{GeV} \leq h$ candidate $M_{jj} \leq 155\text{GeV}$

Event Selection

- Jet clustering : Durham algorithm
$$Y_{ij} = \frac{2\min\{E_i^2, E_j^2\}(1 - \cos \theta)}{E_{\text{cm}}^2}$$

- forced 8 jet clustering for $t\bar{t}\rightarrow 8\text{jets}$ channel
 - ✓ “ $Y_{87} > 0.00055$ ” + “ $Y_{87} \leq 0.00055 \text{ && } Y_{76} > 0.0012$ ”
 - forced 6 jet clustering for $t\bar{t}\rightarrow l\nu+6\text{jets}$ channel
 - ✓ “ $Y_{65} > 0.00165$ ” + “ $Y_{65} \leq 0.00165 \text{ && } Y_{54} > 0.005$ ”

- Isolated Lepton

Definition

$$\begin{aligned}\cos\theta_{\text{cone}} &= 0.98 \\ E_{\text{cone}} &< \sqrt{6(E_{\text{pfo}} - 15)}\end{aligned}$$

- ✓ require no(one) Isolated lepton to 8jet($l\nu+6\text{jet}$) channel
 - ✓ b candidate jets ≥ 4 (b likeness $\geq 0.85, 0.8, 0.6, 0.2$)
 - reject events with very forward jets
 - ✓ $|\text{Jet cos}\theta| \leq 0.99$
 - events with large missing momentum
 - ✓ MP $> 20 \text{ GeV}$

Event Selection

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 - ✓ $|\text{Jet cos}\theta| \leq 0.99$
 - events with large missing momentum
 - ✓ MP $> 20 \text{ GeV}$

Jet pairing, χ^2 Cut

- $\sqrt{s} = 500\text{GeV}$ is near by threshold of the $t\bar{t}$ production

- P_{higgs} should be small

- Dijet angle becomes large

→ Angle information between higgs candidate jets is effective to choose correct jet pair.

- try all combination and choose a pair with minimum χ^2 value

reject large χ^2 events

✓ $\chi^2 \leq 11.2$

$$\chi^2 = \left(\frac{\Delta\text{angle}(j_1, j_2) - \Delta\text{angle}(\text{higgs } jj)}{\sigma_{\Delta\text{angle}(\text{higgs } jj)}} \right)^2 + \left(\frac{m_{j_3 j_4 j_5} - M_{top}}{\sigma_{M_{top}}} \right)^2 + \left(\frac{m_{j_4 j_5} - M_W}{\sigma_{M_W}} \right)^2 + \left(\frac{m_{j_6 j_7 j_8} - M_{top}}{\sigma_{M_{top}}} \right)^2 + \left(\frac{m_{j_7 j_8} - M_W}{\sigma_{M_W}} \right)^2$$

require b likeness ≥ 0.2 to j_1, j_2, j_3, j_6

- Reference values are made from reconstructed jets which are matched with MC information
 - $M_{top} = 171.5\text{GeV}$
 - $\sigma M_{top} = 16.8\text{ GeV}$
 - $M_W = 80.5\text{GeV}$
 - $\sigma M_W = 9.9\text{ GeV}$
 - $\text{angle}(jj) = 2.448$
 - $\sigma \text{angle}(jj) = 0.277$

higgs and top pairing, χ^2 Cut

$$\chi^2 = \left(\frac{\Delta angle(j_1, j_2) - \Delta angle(higgs jj)}{\sigma_{\Delta angle(higgs jj)}} \right)^2 + \left(\frac{m_{j_3 j_4 j_5} - M_{top}}{\sigma_{M_{top}}} \right)^2 + \left(\frac{m_{j_4 j_5} - M_W}{\sigma_{M_W}} \right)^2 + \left(\frac{m_{j_6 l\nu} - M_{top}}{\sigma_{M_{top}}} \right)^2$$

Angle information between higgs candidate jets is effective to choose correct jet pair.

A W mass is reconstructed with Isolated lepton and Missing P

- try all combination and choose a pair with minimum χ^2 value

reject large χ^2 events

✓ $\chi^2 \leq 16.5$

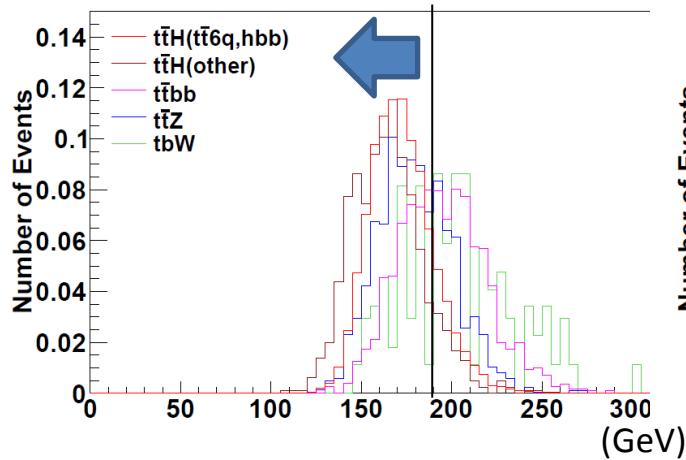
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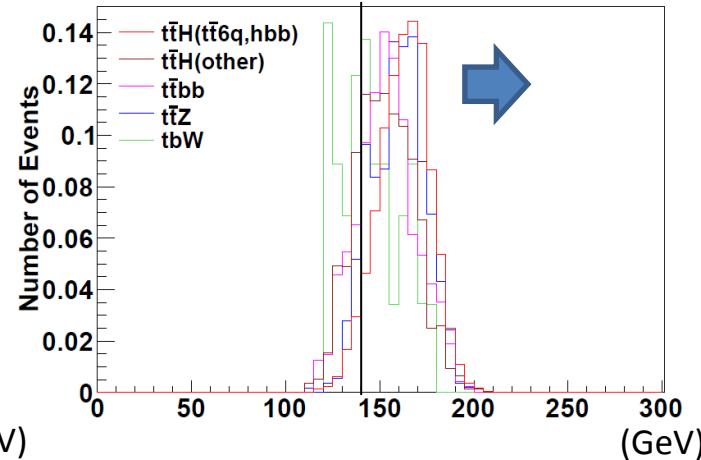
MP, 2 Jet E sum, M_{jjj}(top Mass)

8jet channel

Leading 2 jet energy sum
 < 189 GeV

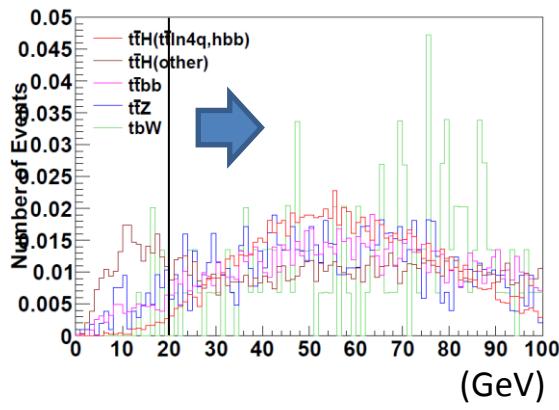


M_{jjj} (top Mass) > 140 GeV

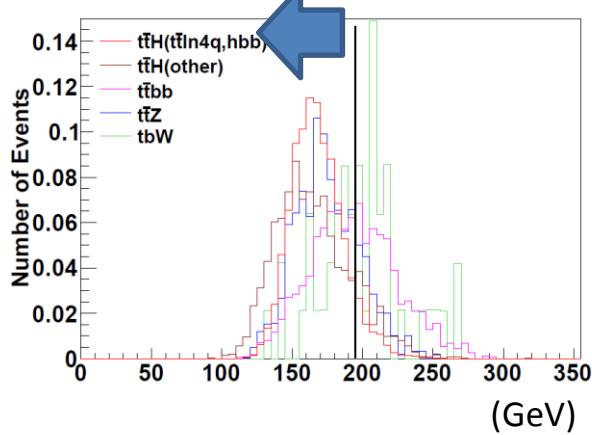


4+6jet channel

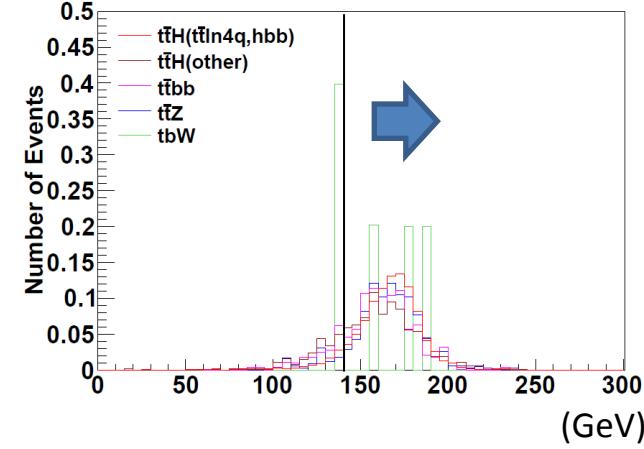
Missing Momentum
 > 20 GeV



Leading 2 jet energy sum
 < 195 GeV



M_{jjj} (top Mass) > 140 GeV



Result of event selection

$t\bar{t}h \rightarrow 8\text{jets}$
Preliminary

Process	# of events
$t\bar{t}h \rightarrow 4q+4b$	14.7
$t\bar{t}h$ (not signal)	0.6
$t\bar{t}Z$	8.7
$t\bar{t}bb$	3.3
$t\bar{b}W$	11.9

- $N_{\text{sig}}(t\bar{t}h \rightarrow 8\text{jtes}) = 14.7$
- $N_{\text{bkgd}} = 24.5$

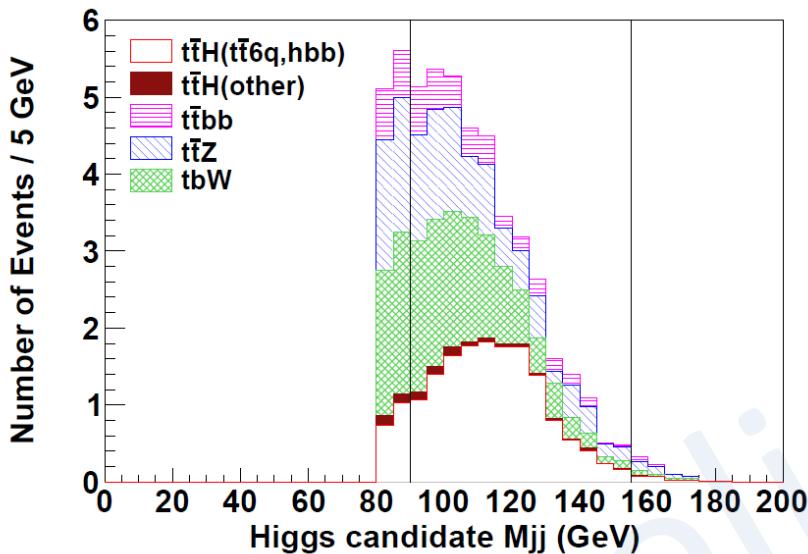
$t\bar{t}h \rightarrow l\nu+6\text{jets}$
Preliminary

Process	# of events
$t\bar{t}h \rightarrow l\nu+2q+4b$	9.77
$t\bar{t}h$ (not signal)	0.4
$t\bar{t}Z$	5.33
$t\bar{t}bb$	1.96
$t\bar{b}W$	5.69

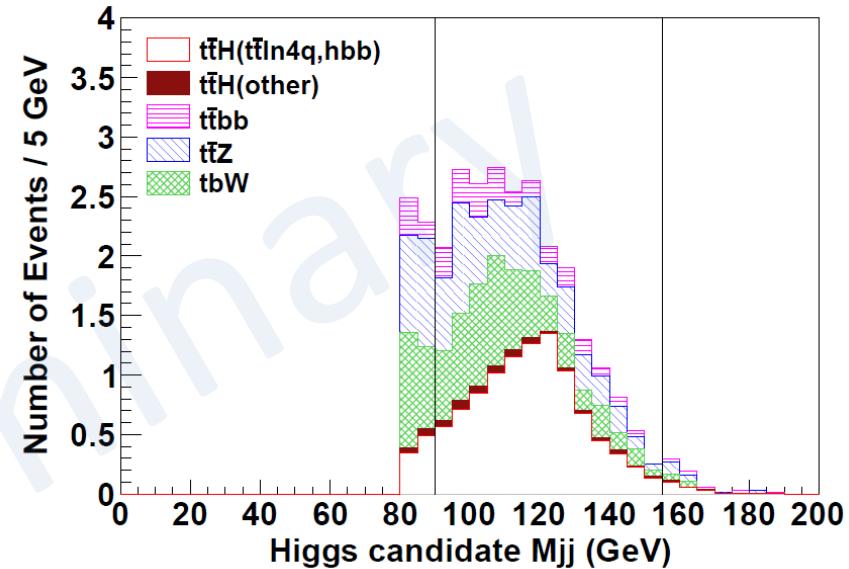
- $N_{\text{sig}}(t\bar{t}h \rightarrow l\nu+6\text{jtes}) = 9.77$
- $N_{\text{bkgd}} = 13.4$

Result of ILD Full Simulation

$t\bar{t}h \rightarrow 8\text{jets}$



$t\bar{t}h \rightarrow l\nu + 6\text{jets}$



- $\sqrt{s} = 500 \text{ GeV}, 500 \text{ fb}^{-1}$
- $N_{\text{sig}} = 14.7$
- $N_{\text{bkgd}} = 24.5$
- $N_{\text{sig}}/\sqrt{N_{\text{sig}} + N_{\text{bkgd}}} = \underline{2.351}$,
- $\sqrt{s} = 500 \text{ GeV}, 500 \text{ fb}^{-1}$
- $N_{\text{sig}} = 9.77$
- $N_{\text{bkgd}} = 13.4$
- $N_{\text{sig}}/\sqrt{N_{\text{sig}} + N_{\text{bkgd}}} = \underline{2.029}$,
- $W \rightarrow e, \mu, \tau + \nu$ inclusive analysis

Systematic uncertainties

$$(\Delta\sigma/\sigma) = \sqrt{\frac{S+B}{S^2} + \left(\frac{\Delta B}{S}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta Br}{Br}\right)^2 + \left(\frac{\Delta Pol}{Pol}\right)^2 + \left(\frac{\Delta \varepsilon}{\varepsilon}\right)^2}$$

statistical systematics

- counting analysis
→ simply consider systematic uncertainties related to # of events
- b tag efficiency and Jet Energy Scale Factor (JESF) will be dominant source of systematic uncertainties.
- assuming $\pm 1\%$ or $\pm 3\%$ uncertainty on JESF and b tag efficiency. (at blikeness = 0.8)

$$E_{jet}^i(syst) = E_{jet}^i(1 + \Delta JESF), i = 1-8.$$

Systematic uncertainties

$$(\Delta\sigma/\sigma) = \sqrt{\frac{S+B}{S^2} + \left(\frac{\Delta B}{S}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta Br}{Br}\right)^2 + \left(\frac{\Delta Pol}{Pol}\right)^2 + \left(\frac{\Delta \varepsilon}{\varepsilon}\right)^2}$$

statistical

systematic
related
Background

$$\left(\frac{\Delta B}{S}\right)^2 = (\Delta B^2(\text{btag}) + \Delta B^2(\text{JESF})) / S^2$$

$$\Delta B^2 = \Delta N_{\text{ttZ}}^2 + \Delta N_{\text{ttbb}}^2 + \Delta N_{\text{tbW}}^2 + \Delta N_{\text{tth(w/o signal)}}^2$$

$$\Delta N = N_{\text{systematic}} - N_{\text{center value}}$$

N: Number of events after event selection

Systematic uncertainties

$$(\Delta\sigma/\sigma) = \sqrt{\frac{S+B}{S^2} + \left(\frac{\Delta B}{S}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta Br}{Br}\right)^2 + \left(\frac{\Delta Pol}{Pol}\right)^2 + \left(\frac{\Delta \varepsilon}{\varepsilon}\right)^2}$$

statistical

systematics related Background

systematic Luminosity

systematic $h \rightarrow bb$ Branching ratio

systematic polarization

$$\left(\frac{\Delta B}{S}\right)^2 = (\Delta B^2(\text{btag}) + \Delta B^2(\text{JESF}))/S^2$$

$$\Delta B^2 = \Delta N_{ttZ}^2 + \Delta N_{ttbb}^2 + \Delta N_{tbW}^2 + \Delta N_{tth(\text{w/o signal})}^2$$

$$\Delta N = N_{\text{systematic}} - N_{\text{center value}}$$

$\left(\frac{\Delta L}{L}\right) \sim 0.1\%$
$\left(\frac{\Delta Br}{Br}\right) \sim 1\%$
$\left(\frac{\Delta Pol}{Pol}\right) \sim 0.1\%$

Systematic uncertainties

$$(\Delta\sigma/\sigma) = \sqrt{\frac{S+B}{S^2} + \left(\frac{\Delta B}{S}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta Br}{Br}\right)^2 + \left(\frac{\Delta Pol}{Pol}\right)^2 + \left(\frac{\Delta \varepsilon}{\varepsilon}\right)^2}$$

statistical

systematics related Background

systematics Luminosity

systematics $h \rightarrow bb$ Branching ratio

systematics polarization

systematics signal event selection

$$\left(\frac{\Delta B}{S}\right)^2 = (\Delta B^2(\text{btag}) + \Delta B^2(\text{JESF}))/S^2$$

$$\left(\frac{\Delta \varepsilon}{\varepsilon}\right)^2 = (\Delta S(\text{btag})/S)^2 + (\Delta S(\text{JESF})/S)^2$$

$$\Delta S^2 = \Delta N^2_{t\bar{t} \rightarrow 8\text{jets}/l\nu+6\text{jets}}$$

$$\Delta N = N_{\text{systematic}} - N_{\text{center value}}$$

$$\left(\frac{\Delta L}{L}\right) \sim 0.1\%$$

$$\left(\frac{\Delta Br}{Br}\right) \sim 1\%$$

$$\left(\frac{\Delta Pol}{Pol}\right) \sim 0.1\%$$

Current status of Systematic uncertainties

b likeness $\pm 1\%$

Jet energy scale factor $\pm 1\%$

b likeness $\pm 3\%$

Jet energy scale factor $\pm 3\%$

tth → 8 jets	blikeness	JESF
signal	2%	1%
ttZ	2%	3%
ttbb	2 %	3%
tbW → 6 jets	2 %	<4 %

tth → 8 jets	blikeness	JESF
signal	6 %	7 %
ttZ	5 %	15 %
ttbb	8 %	5%
tbW	3 %	<15%

tth → lν+6 jets	blikeness	JESF
signal	2%	2 %
ttZ	4%	5 %
ttbb	3%	5 %
tbW → ln+4 jets	<3%	<9%

tth → lν+6 jets	blikeness	JESF
signal	5 %	7 %
ttZ	8 %	14 %
ttbb	7 %	15 %
tbW → ln+4 jets	<4 %	<20 %

Significance and Precision of top-Yukawa coupling measurement with Systematic Uncertainties

- $M_h=125 \text{ GeV}$, $\sqrt{s} = 500 \text{ GeV}$, 500 fb^{-1}
- systematics: b tag eff. $\pm 1,3\%$, JESF $\pm 1,3\%$
 $\text{Br } 1\%$, L 0.1% , pol 0.1%

tth $\rightarrow 8$ Jets

with systematics	signficance	$ \Delta g_t/g_t $
0% (stat. only)	2.351	22.11%
1% (b, JESF)	2.343	22.19%
3% (b, JESF)	2.240	23.2%

tth $\rightarrow l\nu + 6\text{jets}$

with systematics	signficance	$ \Delta g_t/g_t $
0% (stat. only)	2.029	25.62%
1% (b, JESF)	2.019	25.75%
3% (b, JESF)	1.958	26.55%

Rough estimation of
significance and $|\Delta g_{t\bar{t}h}/g_{t\bar{t}h}|$
 $\text{@}\sqrt{s} = 500\text{-}550 \text{ GeV}, 500 \text{ fb}^{-1}$

Combined result of
8jets and 6jets mode

(* syst. error is not included)

\sqrt{s} : $S/\sqrt{S + B}$: $|\Delta g_{t\bar{t}h}/g_{t\bar{t}h}|$ %

500 : 3.105 : 16.74

520 : 5.113 : 10.16

550 : 7.403 : 7.023

cross section (fb)

\sqrt{s} : tth(total) : ttz : ttbb : tbw

500 : 0.485 : 1.974 : 1.058 : 979.8

520 : 0.981 : 2.753 : 1.151 : 953.5

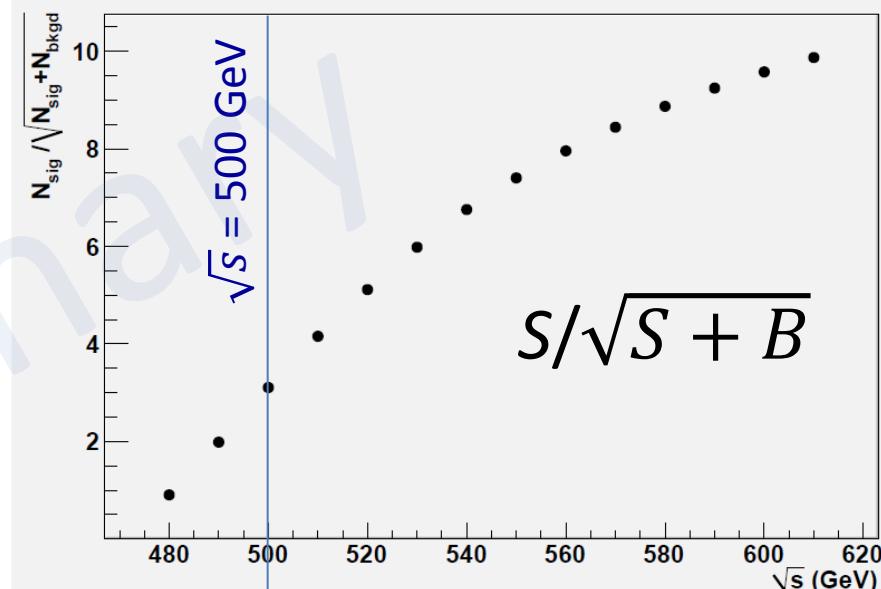
550 : 1.743 : 3.806 : 1.285 : 909.5

- ILC 1600 fb^{-1} at $\sqrt{s} = 500 \text{ GeV}$

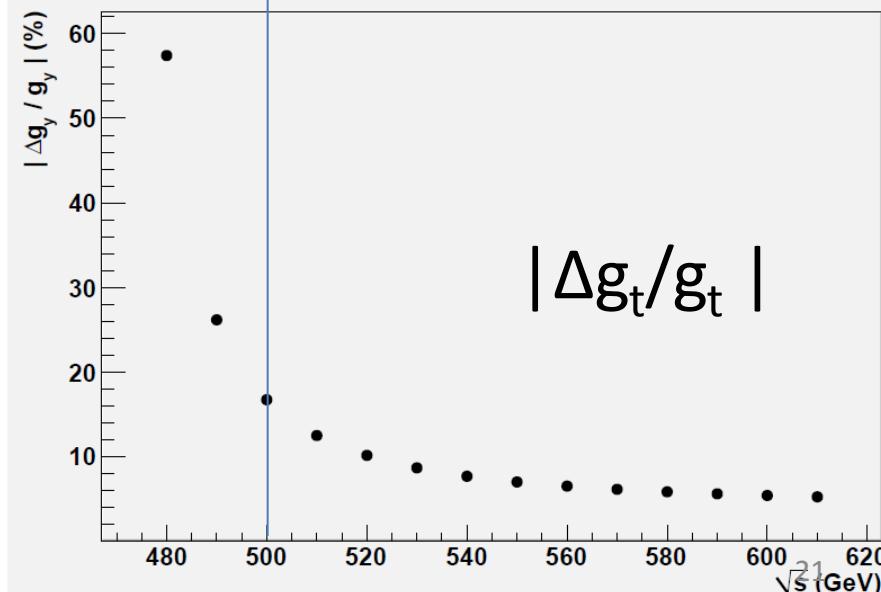
$|\Delta g_{t\bar{t}h}/g_{t\bar{t}h}| \sim 9.48\% \text{ (1% syst. included)}$

9.36% (stat. only)

Graph



Graph



$|\Delta g_t / g_t|$

Summary

- Direct measurement of top Yukawa coupling
- Estimate impact of systematic uncertainties on sensitivity
- Systematic uncertainties are not small,
but statistical uncertainty is dominant in this study.

$\sqrt{s} = 500 \text{ GeV}, 500 \text{ fb}^{-1}, P(e^-, e^+) = (-0.8, +0.3)$

$S/\sqrt{S + B}$ ($|\Delta g_{t\bar{t}h}/g_{t\bar{t}h}|$): stat. only \rightarrow include 1% syst.
 $t\bar{t}h \rightarrow 8\text{jets}$: 2.351 (22.11%) \rightarrow 2.345 (22.17%)
 $t\bar{t}h \rightarrow l\nu + 6\text{jets}$: 2.029 (25.62%) \rightarrow 2.016 (25.79%)

- to improve sensitivity
 - counting analysis \rightarrow MVA
 - $W \rightarrow e, \mu, \tau + \nu$ inclusive analysis \rightarrow separate τ channel
 - Lepton identification
 - $t\bar{t}h \rightarrow l\nu l\nu + 4b$ channel
 - $h \rightarrow WW, h \rightarrow \tau\tau$ channel

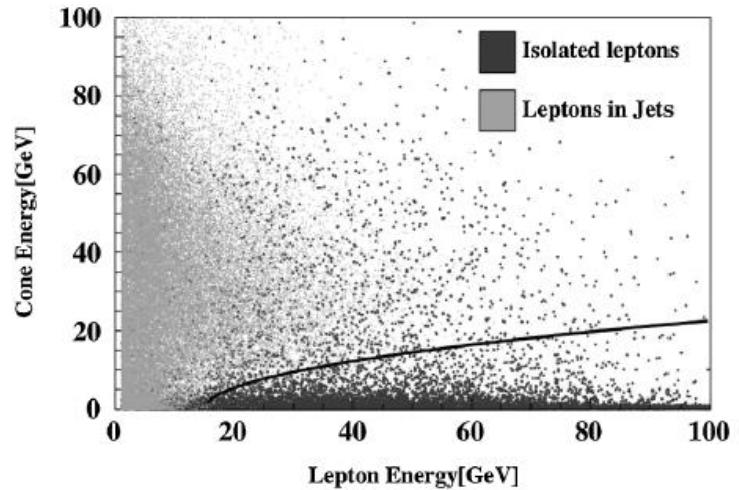
Backup

Isolated Lepton

- Isolated Lepton

Definition

$$\cos\theta_{\text{cone}} = 0.98$$
$$E_{\text{cone}} < \sqrt{6(El - 15)}$$



Systematic uncertainties on tbW events

$$\left(\frac{\Delta B}{S}\right)^2 = (\Delta B^2(\text{btag}) + \Delta B^2(\text{JESF}))/S^2$$

- in signal category (4 b tagged), 0~a few MC events are passed all event selection
- too low statistics to estimate systematic uncertainty

I used 2 b tagged category to estimate uncertainty on tbW background event selection.

In this analysis, definition of $\Delta N(\text{tbW}, 4\text{btag})$ is

- $\Delta N(\text{tbW}, 4\text{btag}) = N(\text{tbW}, 4\text{btag}) \times \left(\frac{\Delta N(\text{tbW}, 2\text{btag})}{N(\text{tbW}, 2\text{btag})} \right)$

Mjj shape of tbW events ($t\bar{t}h \rightarrow l\nu 6\text{jets}$)

AWLC2014

- tbw event shape is difficult to estimate with 4 b tag category due to the small statistics of MC samples.
- compare Mjj shape of 2 b tag category and 4 b tag category
 - **2 b tag category**: Y_{65} cut
 - 4 b tag category: Y_{65} cut and Y_{54}
- check Mjj shape of ttz and ttbb events
- In $\text{Mjj} \geq 80 \text{ GeV}$, the Mjj shapes of 2 b tag category are similar to 4 b tag category.
ttz : KS probability = 0.43 (good)
ttbb : KS probability = 0.087 (not bad)
- ✓ We use Mjj shape of tbW events in 2 b tag category
- ✓ higgs candidate $\text{Mjj} \geq 80 \text{ GeV}$

