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# Impact of Systematic Uncertainties on the Top Yukawa Coupling Measurement

ILD Meeting at Oshu

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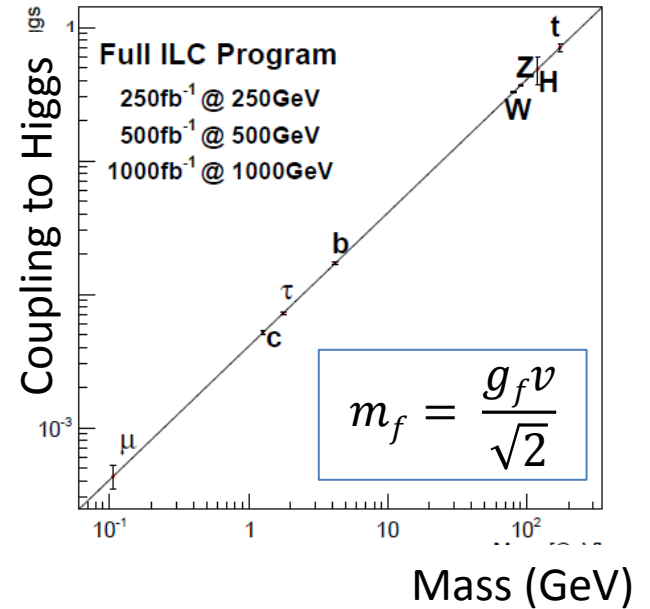
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# Introduction

- We can directly measure the top-Yukawa coupling via tth channel at  $\sqrt{s} = 500$  GeV.
- We are working on tth study assuming
  - $M_h = 125$  GeV.
  - Polarization :  $(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$
  - Integrated luminosity  $500 \text{ fb}^{-1}$
- ILD full simulation

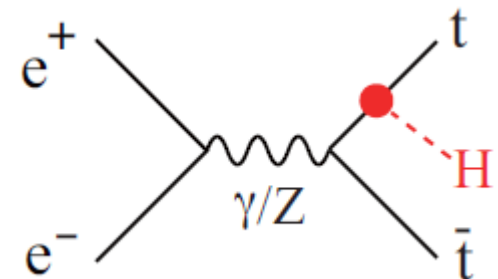


## Signals

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

## Main Backgrounds

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



# expected # of events @ 500fb<sup>-1</sup>

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

| Process                      | $\sigma$ (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<sup>-1</sup>)

|                       |             |                         |             |
|-----------------------|-------------|-------------------------|-------------|
| <b>tth(tt6j, hbb)</b> | <b>63.9</b> | <b>tth(ttlv4j, hbb)</b> | <b>61.3</b> |
| tth(ttall, hnobb)     | 102.6       | ttZ                     | 987         |
| tth(ttlvlv2j, hbb)    | 14.6        | ttg(bb)                 | 529         |
|                       |             | tbW                     | 489902      |

# tth $\rightarrow$ 8jets(lv+6jets) analysis

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

In this analysis, higgs decays into two b jets

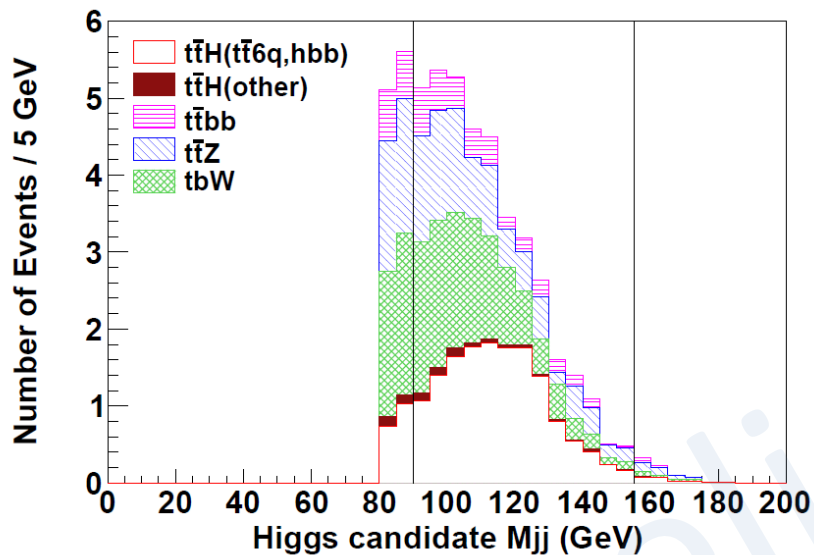
- 4 b jets out of 8(6) jets
- No (one) isolated lepton
- Use Kt clustering only for removing low Pt background

## Event Selection

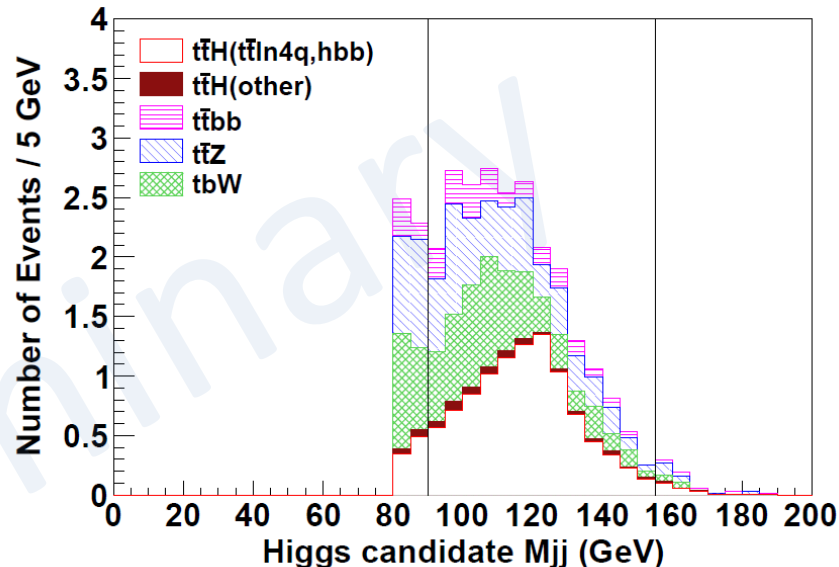
- signal topology
  - ✓ Y cut (6, 8 jet event)
  - ✓ No(one Isolated Lepton)
  - ✓ B jet candidate  $\geq 4$
- detector acceptance
  - $|\text{Jet } \cos\theta| \leq 0.99$
- jet pairing
  - ✓  $\chi^2 \leq 11.2$  (16.5)
- kinematics
  - ✓ Leading 2 Jet Energy Sum
  - ✓ Lowest 3 Jet Energy Sum (for 8jets 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  $M_{jj} \leq 155\text{GeV}$

# Full Simulation Result

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



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



- $\sqrt{s} = 500 \text{ GeV}, 500 \text{ fb}^{-1}$
- $N_{\text{sig}} = 14.73$
- $N_{\text{bkgd}} = 24.52$
- $N_{\text{sig}} / \sqrt{N_{\text{sig}} + N_{\text{bkgd}}} = \underline{2.351}$ ,

- $\sqrt{s} = 500 \text{ GeV}, 500 \text{ fb}^{-1}$
- $N_{\text{sig}} = 9.768$
- $N_{\text{bkgd}} = 13.41$
- $N_{\text{sig}} / \sqrt{N_{\text{sig}} + N_{\text{bkgd}}} = \underline{2.029}$ ,

- $W \rightarrow e, \mu, \tau + \nu$  inclusive analysis

# Systematic uncertainties

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

statistical

**systematics**

- counting analysis  
→ simply consider systematic uncertainties related to # of events
- blikeness and Jet Energy Scale Factor (JESF) will be dominant source of systematic uncertainties.
- assuming  $\pm 1\%$  or  $\pm 3\%$  uncertainty on blikeness and JESF.  
 $E_{jet}^i(\text{syst}) = E_{jet}^i(1 + \Delta\text{JESF})$ ,  $i = 1-8$ .  
Same procedure as  $E_{jet}(\text{syst})$  is applied to estimate blikeness syst.

# Systematic uncertainties

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

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→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→bb Branching ratio
systematics polarization
**systematics signal event selection**

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

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

$$\Delta S^2 = \Delta N^2_{\text{tth} \rightarrow 8\text{jets}/\text{lv}+6\text{jets}}$$

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

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

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

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

# 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 $\rightarrow$ 8 jets | blikeness | JESF |
|--------------------------|-----------|------|
| signal                   | 1%        | 1%   |
| ttZ                      | 1%        | 3%   |
| ttbb                     | 1%        | 3%   |
| tbW $\rightarrow$ 6jets  | <2 %      | <4 % |

| tth $\rightarrow$ 8 jets | blikeness | JESF |
|--------------------------|-----------|------|
| signal                   | 2 %       | 7 %  |
| ttZ                      | 2 %       | 15 % |
| ttbb                     | 3 %       | 5%   |
| tbW                      | <4 %      | <15% |

| tth $\rightarrow$ lv+6jets | blikeness | JESF |
|----------------------------|-----------|------|
| signal                     | 1%        | 2 %  |
| ttZ                        | 2%        | 5 %  |
| ttbb                       | 2%        | 5 %  |
| tbW $\rightarrow$ ln+4jets | <3%       | <9%  |

| tth $\rightarrow$ lv+6jets | blikeness | JESF  |
|----------------------------|-----------|-------|
| signal                     | 2 %       | 7 %   |
| ttZ                        | 5 %       | 14 %  |
| ttbb                       | 5 %       | 15 %  |
| tbW $\rightarrow$ ln+4jets | <4 %      | <20 % |

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

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

tth  $\rightarrow$  8 Jets

| with systematics | significance | $ \Delta g_t/g_t $ |
|------------------|--------------|--------------------|
| 0% (stat. only)  | 2.351        | 22.11%             |
| 1% (b, JESF)     | 2.345        | 22.17%             |
| 3% (b, JESF)     | 2.252        | 23.09%             |

tth  $\rightarrow$  lv+6jets

| with systematics | significance | $ \Delta g_t/g_t $ |
|------------------|--------------|--------------------|
| 0% (stat. only)  | 2.029        | 25.62%             |
| 1% (b, JESF)     | 2.016        | 25.79%             |
| 3% (b, JESF)     | 1.965        | 26.46%             |

# Rough estimation of

significance and  $|\Delta g_t/g_t|$

@ $\sqrt{s} = 480-610$  GeV,  $500 \text{ fb}^{-1}$

8 jets & 1v6jets combined result  
(with only statistical uncertainty)

$\sqrt{s}$  :  $S/\sqrt{S+B}$  :  $|\Delta g_t/g_t|$  %

490 : 1.985 : 26.18

500 : 3.105 : 16.74

510 : 4.156 : 12.51

520 : 5.113 : 10.16

530 : 5.983 : 8.691

540 : 6.755 : 7.697

550 : 7.403 : 7.023

cross section (fb)

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

490 : 0.272 : 1.569 : 1.009 : 991.1

500 : 0.485 : 1.974 : 1.058 : 979.8

510 : 0.725 : 2.373 : 1.105 : 967.0

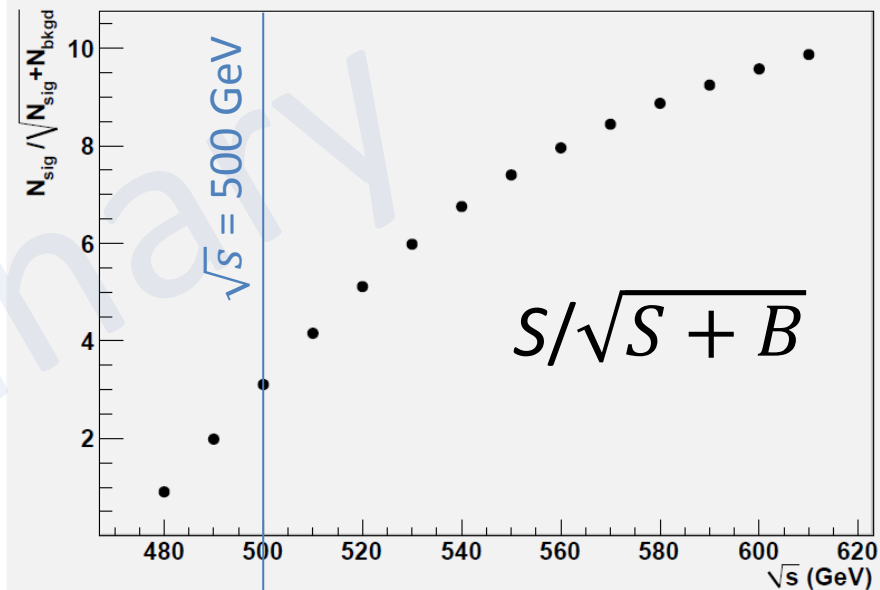
520 : 0.981 : 2.753 : 1.151 : 953.5

530 : 1.244 : 3.118 : 1.199 : 939.4

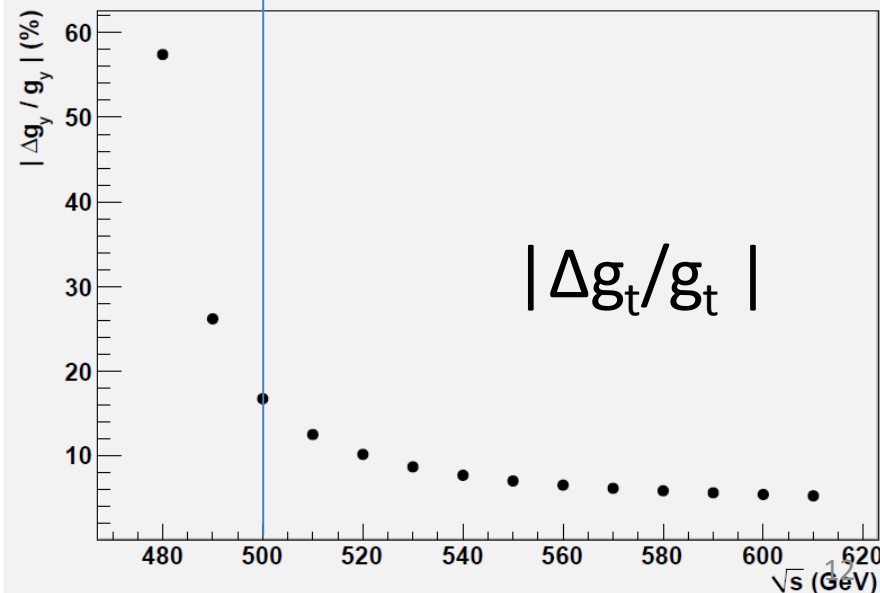
540 : 1.504 : 3.469 : 1.243 : 924.5

550 : 1.743 : 3.806 : 1.285 : 909.5

Graph



Graph



# top Yukawa coupling measurement @ILC and HL-LHC

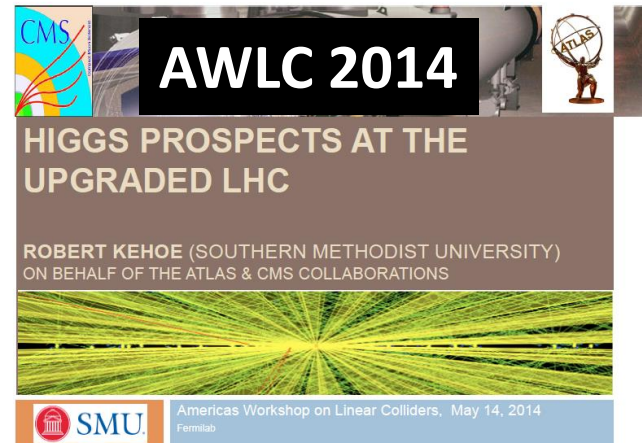
- Cut base event selection & counting analysis
- ILC 500 fb<sup>-1</sup>

|            |   |                |   |                    |   |
|------------|---|----------------|---|--------------------|---|
| $\sqrt{s}$ | : | $S/\sqrt{S+B}$ | : | $ \Delta g_t/g_t $ | % |
| 500        | : | 3.105          | : | 16.74              |   |
| 520        | : | 5.113          | : | 10.16              |   |
| 550        | : | 7.403          | : | 7.023              |   |

- ILC 1600fb<sup>-1</sup> at  $\sqrt{s} = 500$  GeV  
 $|\Delta g_t/g_t| \sim 9.4\%$

\*Number of signals and backgrounds scaled by a factor of 1600fb<sup>-1</sup>/500fb<sup>-1</sup>.

- HL-LHC 3000fb<sup>-1</sup> at  $\sqrt{s} = 14$  TeV  
ATLAS 9-20% (individual 3 channels)  
CMS 7-10 %



# Summary

- estimate impact of systematic uncertainties on sensitivity
- systematic uncertainties are not small, but statistical uncertainty is dominant in this study.

$S/\sqrt{S+B}$  ( $|\Delta g_t/g_t|$ ): stat. only  $\rightarrow$  1% syst. on JESF and blikeness

|                             |                  |               |                |
|-----------------------------|------------------|---------------|----------------|
| tth $\rightarrow$ 8jets     | : 2.351 (22.11%) | $\rightarrow$ | 2.345 (22.17%) |
| tth $\rightarrow$ lv+6jets: | 2.029 (25.62%)   | $\rightarrow$ | 2.016 (25.79%) |

- There are still room to improve tth analysis
  - counting analysis and cut base event selection  $\rightarrow$  MVA
  - $W \rightarrow e, \mu, \tau + \nu$  inclusive analysis  $\rightarrow$  separate hadronic tau
  - Lepton identification
  - $h \rightarrow WW$  channel

# Backup

# 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

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



# Event Selection (tth → 8jets)

- 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

Select events with large  $Y_{87}$  as 8jets category

if  $Y_{87}$  is small, we use  $Y_{76}$  value

✓ “ $Y_{87} > 0.00055$ ” + “ $Y_{87} \leq 0.00055 \ \&\& \ Y_{76} > 0.0012$ ”

- Isolated Lepton

Definition

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

✓ require no Isolated lepton

✓ b candidate jets  $\geq 4$  (b likeness  $\geq 0.85, 0.8, 0.6, 0.2$ )

- reject events with forward jets

✓  $|\text{Jet } \cos\theta| \leq 0.99$

# Jet pairing, $\chi^2$ Cut

- $\sqrt{s} = 500\text{GeV}$  is near by threshold of the  $t\bar{t}h$  production
  - $P_{\text{higgs}}$  should be small
  - Dijet angle becomes large
- Angle information between higgs candidate jets is effective to choose correct jet pair.

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

require b likeness  $\geq 0.2$  to  $j_1, j_2, j_3, j_6$

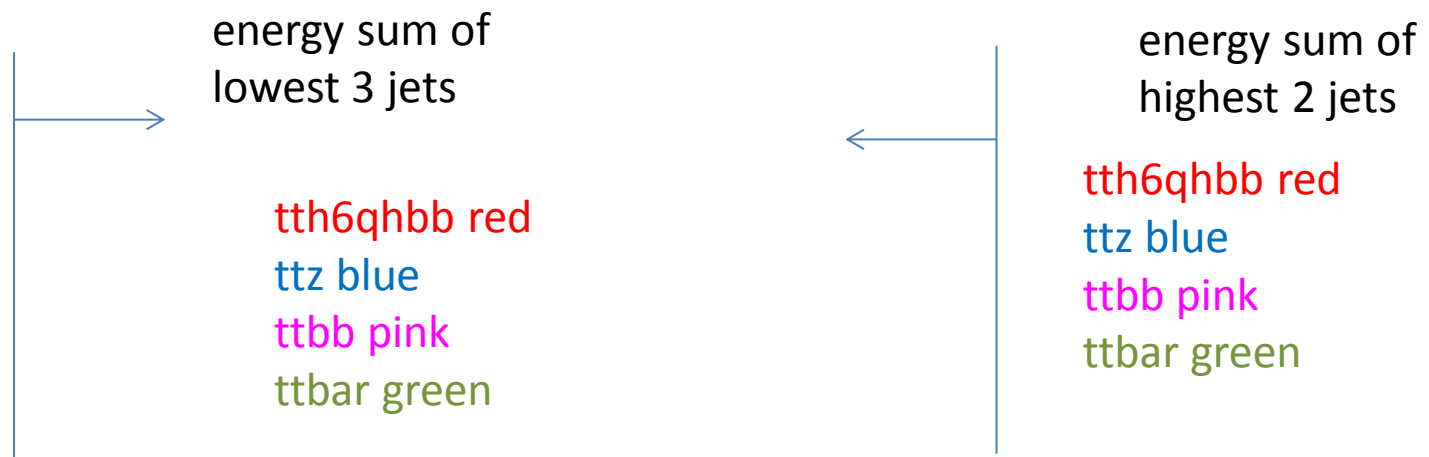
- try all combination and choose a pair with minimum  $\chi^2$  value

reject large  $\chi^2$  events

✓  $\chi^2 \leq 11.2$

# Jet Energy, $M_{\text{top}}$ and $M_{\text{H}}$ range (8jets)

- ttg(bb) and tbW events are assumed to have high energy jets related to top decay.
- ttg(bb) events also have low energy jets related to g
- ✓ energy sum of lowest 3 jets  $> 72$  GeV
- ✓ energy sum of highest 2 jets  $< 189$  GeV
- ✓ top candidate  $M_{\text{H}} \geq 140$  GeV
- select a range of higgs candidate  $M_{\text{H}}$  to maximize  $S/\sqrt{S+B}$
- ✓  $90$  GeV  $\leq$  higgs candidate  $M_{\text{H}} \leq 155$  GeV



# Event Selection ( $t\bar{t}h \rightarrow l\nu + 6\text{jets}$ )

- select 6 jets event

✓ b candidate jets  $\geq 4$  (b likeness  $\geq 0.85, 0.8, 0.6, 0.2$ )

forced 6 jet clustering

Select events with large  $Y_{65}$  as 6jets category

if  $Y_{65}$  is small, we use  $Y_{54}$  value

✓ " $Y_{65} > 0.00165$ " + " $Y_{65} \leq 0.00165 \ \&\& \ Y_{54} > 0.005$ "

- Isolated Lepton

$$\cos\theta_{\text{cone}} = 0.98$$

$$E_{\text{cone}} < \sqrt{6(E_{\text{lep}} - 15)}$$

✓ require exact one isolated lepton

✓ b candidate jets  $\geq 4$  (b likeness  $\geq 0.85, 0.8, 0.6, 0.2$ )

- reject events with forward jets

✓  $|\text{Jet } \cos\theta| \leq 0.99$

- events with large missing momentum

✓  $MP > 20 \text{ GeV}$

# higgs and top pairing, $\chi^2$ Cut

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

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

A W mass is reconstructed with Isolated lepton and Missing P

require b likeness  $\geq 0.2$  to  $j_1, j_2, j_3, j_6$

- try all combination and choose a pair with minimum  $\chi^2$  value

reject large  $\chi^2$  events

✓  $\chi^2 \leq 16.5$

# Jet Energy, $M_{\text{top}}$ and $M_{\text{H}}$ range

- ttg(bb) and tbw events are assumed to have high energy jets related to top decay.
- ttg(bb) events also have low energy jets related to g
- ✓ energy sum of lowest 2 jets > 58 GeV
- ✓ energy sum of highest 2 jets < 195 GeV
- ✓ top candidate  $M_{\text{H}}(M_{\text{H}}) \geq 140$  GeV
- select a range of higgs candidate  $M_{\text{H}}$  to maximize  $S/\sqrt{S+B}$
- ✓  $90 \text{ GeV} \leq \text{higgs candidate } M_{\text{H}} \leq 155 \text{ GeV}$

