Higgs Self Coupling Analysis using the events containing H→WW* decay

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Components for better results (in General)

- Basic components for better sensitivity
  - Lepton ID: Isolated leptons can be identified well, and very good fake suppression

    →many idea have been introduced
  - B-tagging: better b-tagging algorithm provides better background suppression
  - Jet pairing: good jet pairing can obtain good kinematic variables, which leads to good background suppression
  - Good energy & momentum resolution: of course, but limited by the detector performance

    →particle ID will be the key to energy correction
  - Jet clustering: jet reconstruction is the key to the analysis, but it is difficult
  - Good background rejection: of course main theme in analyses
    - Of course, MVA will be a main tool
    - →Focus on Kinematic fitter
- All the components are related each other

Kinematic Fitter for all hadronic @500GeV

- Determining the kinematics globally in the events
  - Distort the event kinematics to meet the constraint in specific process
  - Estimate how much is a event likely to the specific process?
  - Mass resolution will be improved by using χ^2 (or −2log(likelihood)) minimization

- Trying kinematic fitter to all hadronic events
  - Largest cross section
  - Difficult to reject backgrounds
  - Is Kinematic fitter good tool for background rejection?

- ZHH→(bb)(bb)(WW*)→(bb)(bb)(jjjj) kinematic fitter
  - Constraints:

    $m(bb) = m_Z$

    $Max(m1(jj), m2(jj)) = m_W$

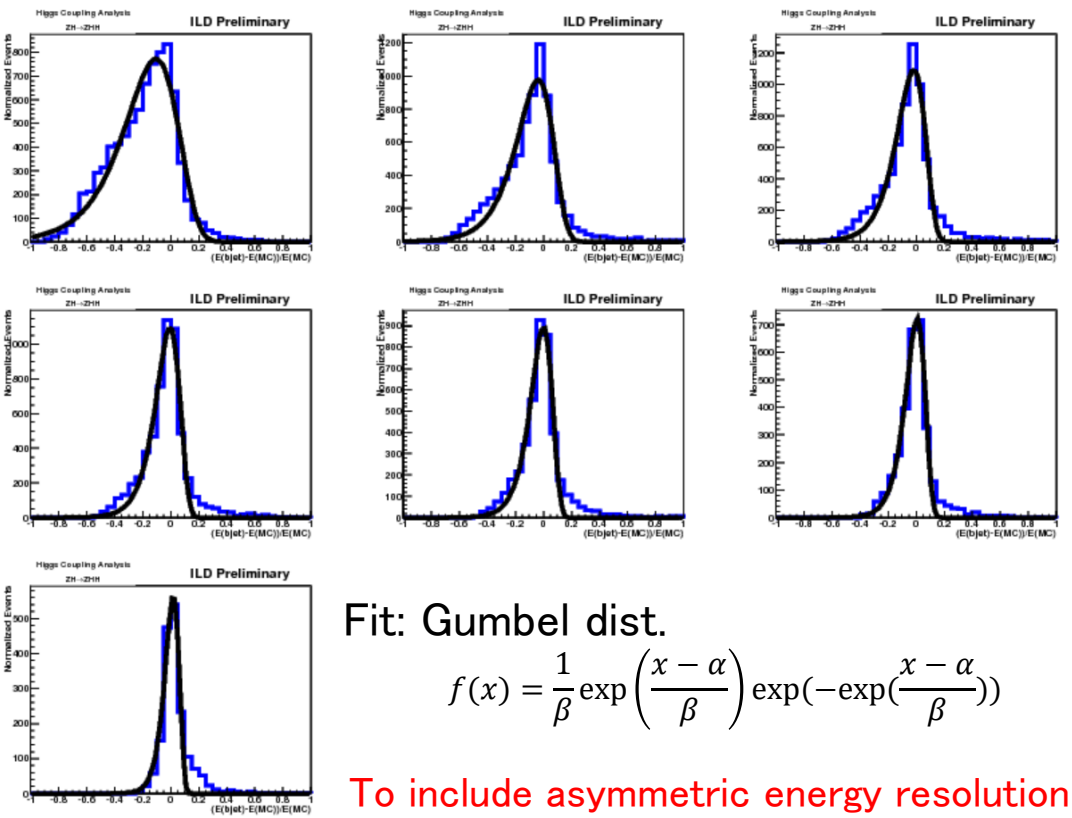
    $m(bb) = m(jjjj)$

    $E(H) + E(Z) + E(jj) + E(jj) = \sqrt{s}$

    $\overrightarrow{p_H} + \overrightarrow{p_Z} + \overrightarrow{p_{jj}} + \overrightarrow{p_{jj}} = \vec{0}$
  - No ISR effect is included…

JET ENERGY RESOLUTION

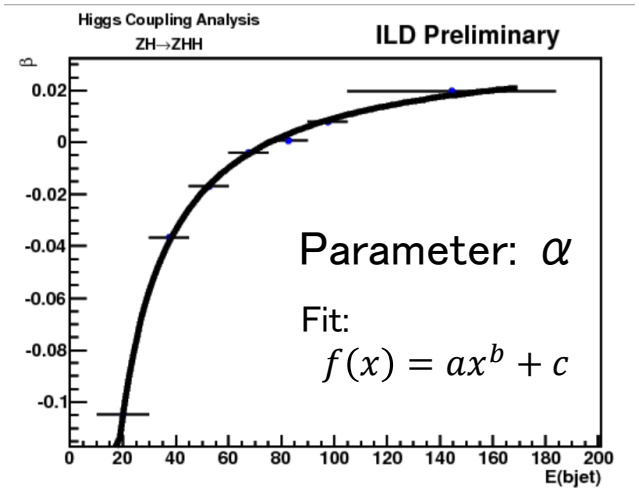
- Most critical factor which degrades mass resolution is jet energy resolution
  - So it is necessary to include this effect into Kinematic fitter
  - Jet energy resolution has energy dependence of jets
    - Parameterize fit parameters with jet energy
  - e.g.) bjet energy resolution

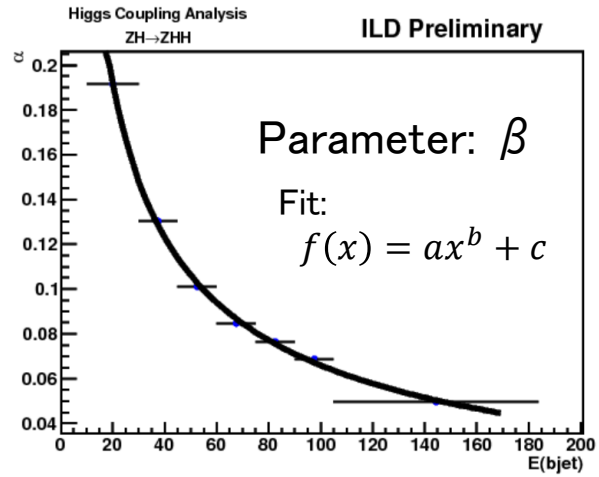


Fit: Gumbel dist.

$$f(x) = \frac{1}{\beta}\exp\left(\frac{x-\alpha}{\beta}\right)\exp(-\exp(\frac{x-\alpha}{\beta}))$$

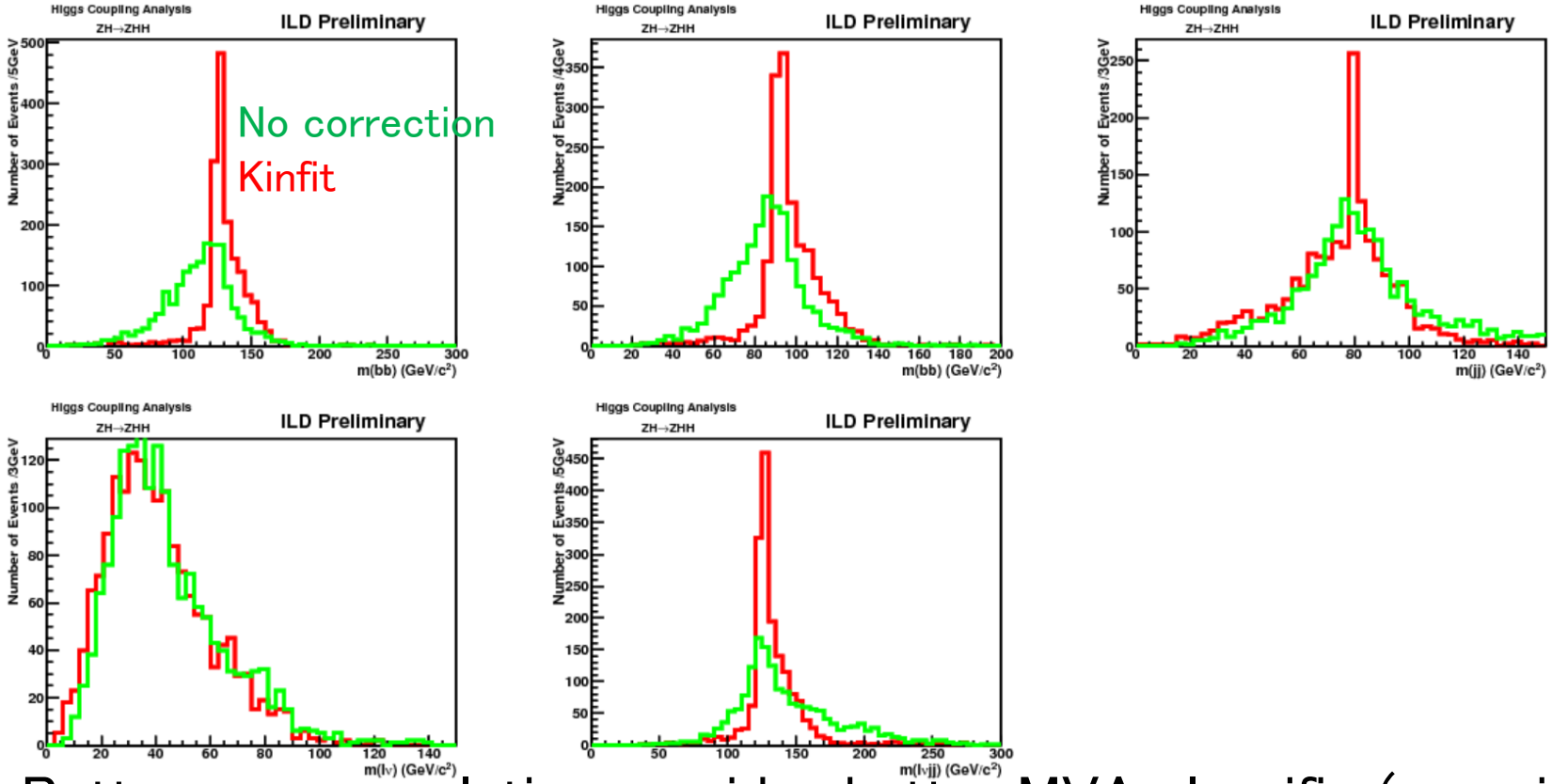
To include asymmetric energy resolution





PERFORMANCE CHECK

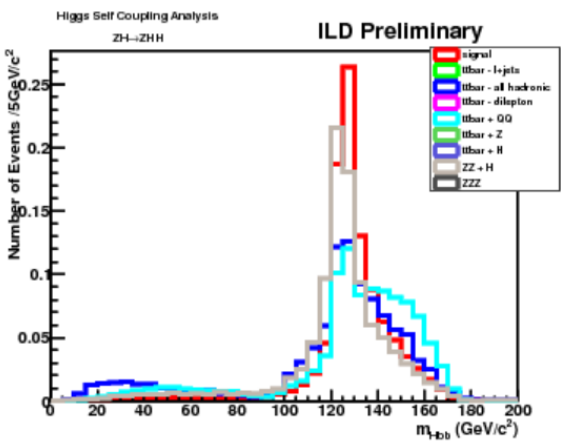
- Check each resonance distribution:
  - Mass resolution is going better! →promising

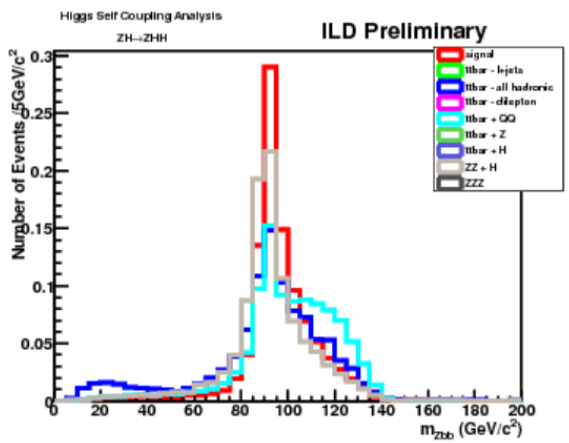


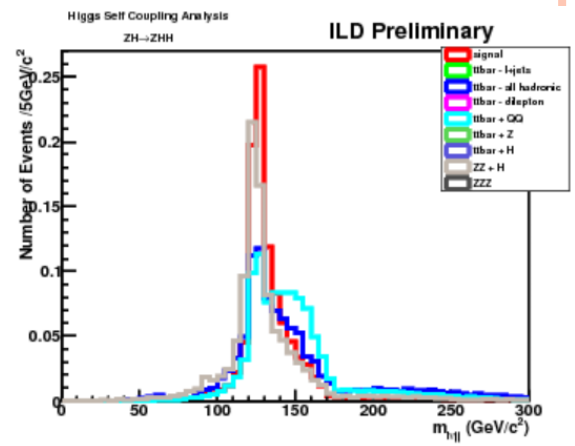
- Better mass resolution provides better MVA classifier(even if backgrounds come in signal mass region)… →same in ILC?
  - c.f.) @CDF, 15% mass resolution improvement→10% improvement of sensitivity for Higgs search

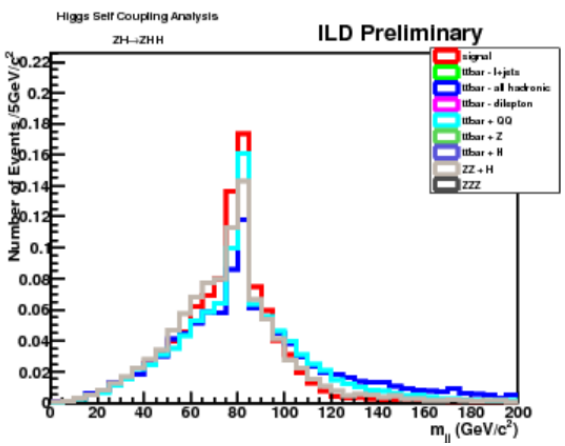
Comparison between signal and backgrounds

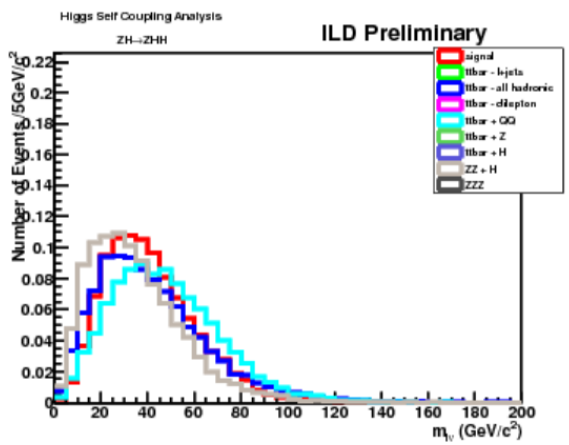
- Higgs mass(H→bb) & Z mass distribution
  - How are mass distributions of backgrounds?
  - ZZH background is hard to reject?
  - Top related backgrounds will be separated well











Signal
ttbar allhadronic
ttbar+QQ
ZZ+H

B-Tagging

- Trying to gain the total acceptance
  - Make b-tagging loosen and categorize using b-tagging condition

- ZHH→(bb)(bb)(WW): maximum number of b-tagging available is **4**

- Making 3-btag category:
  - 4 b-tag caterory: 4 jets with b-likeliness>0.4(0.35) in an event
  - 3 b-tag category: 3 jets with b-likeliness>0.4(0.35) in an event

- We can apply this categorization to:
  - ZHH→(bb)(bb)(l ν jj): Lepton+6jetys
  - ZHH→(bb)(bb)(jjjj): 8jets

Preliminary results@500GeV

- Higgs-strahlung process, ZHH→(bb)(bb)(WW)
- 4 b-tagging or 3 b-tagging
- Calculate the significance, $\frac{s}{\sqrt{s+b}}$
- L=4ab^{-1}(H-20 scenario)

Category	b-tag	Signal	Background	Significance
8jets	4	31.46	232.10	1.94 σ
8jets	3	18.57	925.69	0.60 σ
Lepton+ 6jets	4	3.44	29.12	0.60 σ
Lepton+ 6jets	3	2.08	7.17	0.68 σ

Why???

- Why lepton+6jets 3 b-tag result is better?
  - Originally, signal and background kinematics is very different in this category

→more signal events will lead to better result

Comparison with old results

- Compare with old results
- Calculate the significance, $\frac{s}{\sqrt{s+b}}$
- For comparison, L=2ab^{-1}

Category	b-tag	Old result	New result	
8jets	4	1.50 σ (LCWS13)	1.37 σ (Now)	← Why???
8jets	3	0.35 σ (LCWS13)	0.41 σ (Now)	← 16% improvement
Lepton+ 6jets	4	0.41 σ (LCWS14)	0.43 σ (ALCW15)	← 5% improvement
Lepton+ 6jets	3	N/A	0.48 σ (Now)	← New!

- Why does 8jets 4 b-tag result become worse?
  - Due to lepton ID improvement?

  →more ttbar all hadronic events move into this category

  →become more difficult to reject ttbar backgrounds?
  - Yes, ttbar rejection becomes harder
- Kinematic Fitter provides 5-16% improvement for those modes

Summary and plan

- Higgs self coupling analysis using the events with H→WW* is ongoing.
  - Kinematic fitting will be a good tool for mass resolution improvement
  - Apply it to all hadronic mode and Lepton + jets mode@500GeV
  - Kinematic fitter provides 5%–16% improvement to those modes

  →seems same effect as CDF case in terms of mass resolution improvement

- **Plan:**
  - Include ISR effect in Kinematic fitter
  - Basic analysis components need improvement
    - We already have had many improvements of analysis components in individual study level
    - Especially, flavor tagging will become better
  - Jet clustering is the last key to obtain better result

  →better jet energy resolution gives us better kinematics in an event
  - Finally, incorporate all the improvements and update the self-coupling result!

AT LCWS15

- Will summarize Higgs self-coupling
  - News from HH→(bb)(bb)@500GeV
  - BSM from Higgs Self-coupling
  - News from Junping?

- OK?

BACKUPS

INTRODUCTION

- Measuring the Higgs self coupling is the key point to prove the electroweak symmetry breaking mechanism
  - Higgs potential in SM:

$$V = \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

Mass term

Trilinear coupling

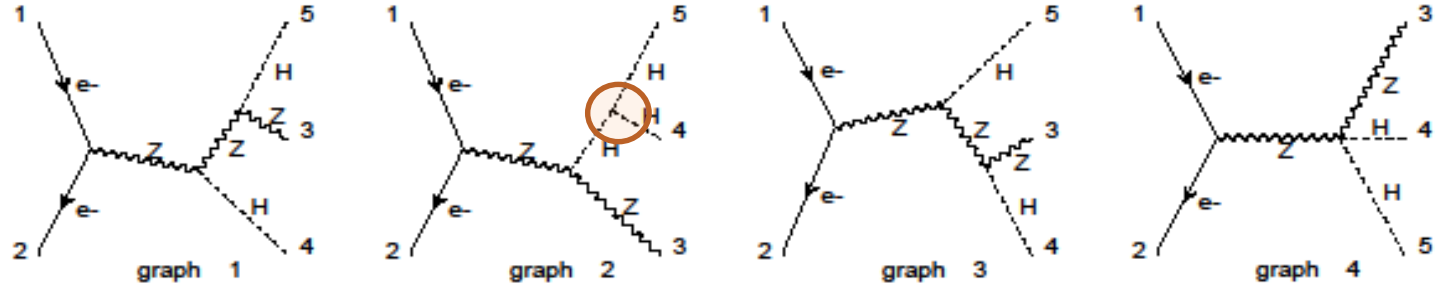
Quartic coupling
→difficult to measure

$$SM: \quad \lambda = \frac{m_H^2}{2v^2} \qquad v \sim 246 GeV$$

- Observing two Higgs bosons in the event is the only way to measure the self coupling
- Accurate test of the coupling may lead to the extended nature of Higgs sector → may go to new physics
- Our goal is to observe and measure the Higgs self coupling first

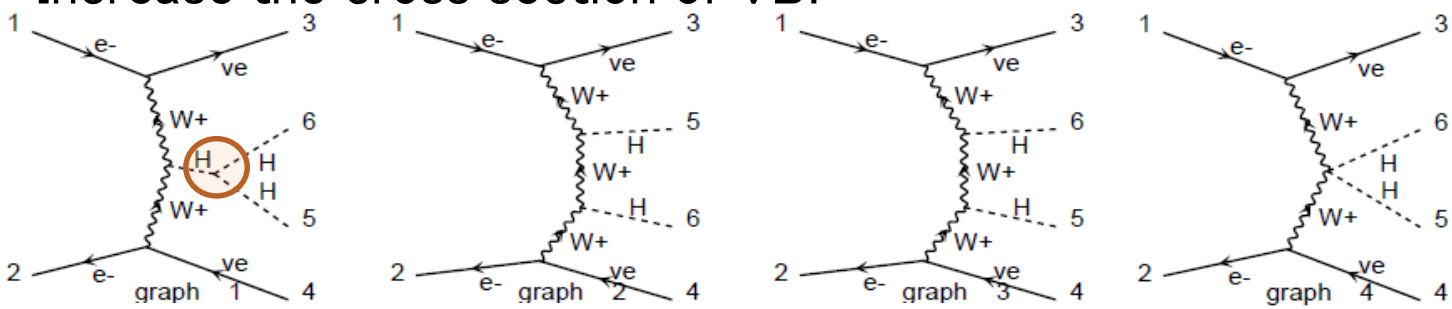
Signal Events

- Signal@500GeV – $e^+e^- \to Z^* \to ZH \to ZHH$ can be used



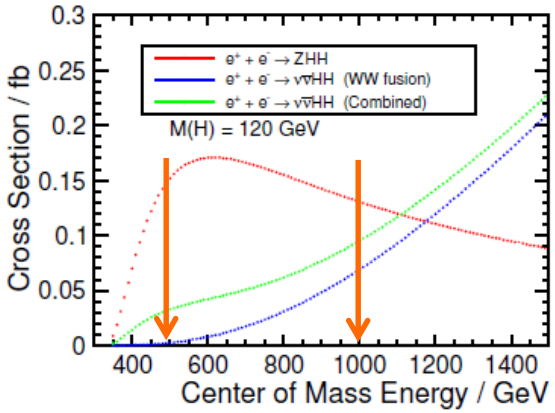
Signal: 2 Irreducible B.G.: 1, 3, 4

- Signal@1TeV – VBF $e^+e^- \to \nu\ \nu$ HH channel is opened
  - Increase the cross section of VBF



Signal:1 Irreducible B.G.: 2, 3, 4

- Higgs decay modes:
  - HH→(bb)(bb): golden channel thanks to b-tag
  - HH→(bb)(WW): improve the final result



Backgrounds and simulation

- Backgrounds considered:

B.G. Process	Feature	Basic idea for rejection
ttbar ZWW	Huge number of events	Flavor tagging Kinematics topology Difference of the final states
ttbar + X	b-jet rich in the final states Similar final states	Kinematics topology
Triple boson • ZZ + H • ZZZ	Small cross section b-jet rich in the final states	Kinematics topology Difference of the final states

S/B ~ 1/3000@500GeV, 1/1000@1TeV

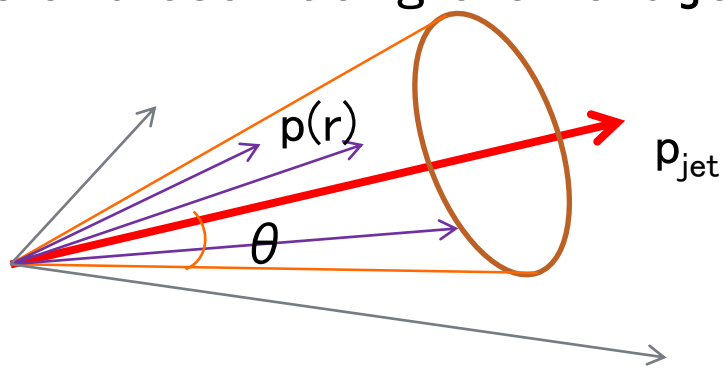
process	σ(fb)	σ(fb)
Signal(inclusive)	0.2	0.3
ttbar & ZWW	581.8	264.9
ttbar + QQ	0.83	5.74
ttbar + Z	0.98	7.81
ttbar + H	0.14	3.22
Z, ν ν + ZH	0.77	2.70
Z, ν ν + ZZ	1.83	14.01

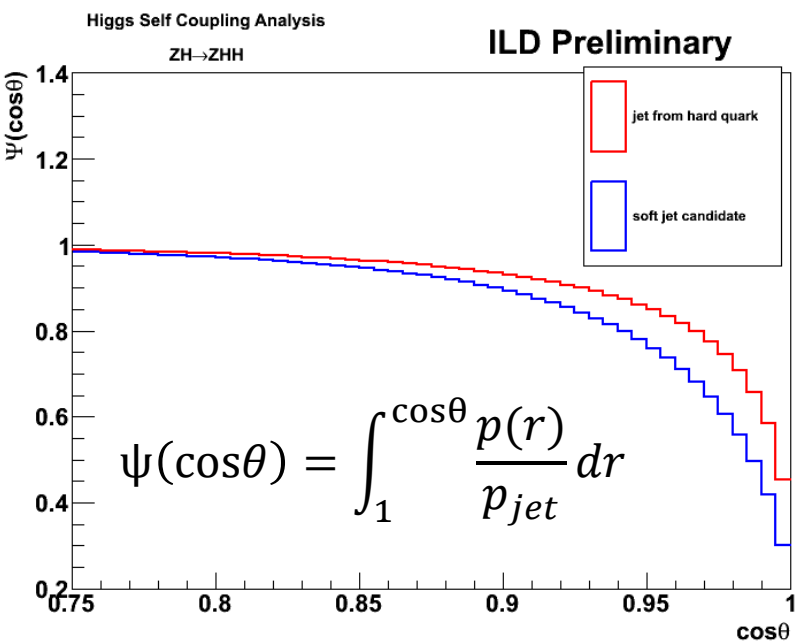
- Simulation

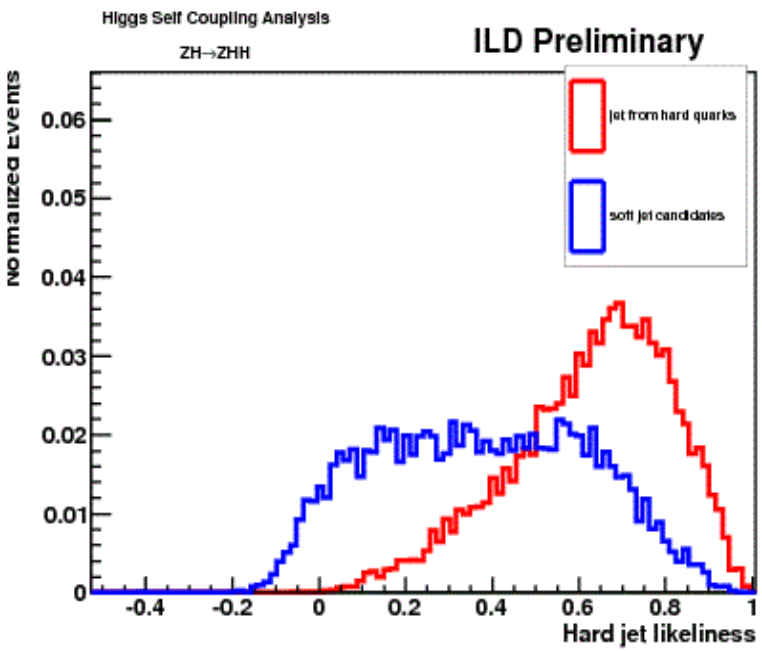
	500GeV	1TeV
Polarization (e,p)	(−0.8,+0.3)	(−0.8,+0.2)
m_H(GeV/c^2)	125	125
simulator	Full(DBD)	Full(DBD)

Soft jet finding

- Tracks in the gluon jets spread wider than those in quark jets(e.g. analyses on hadron collider)
  - Traditional jet shape can be a good estimator
- Using Multivariate Analysis and estimating the hard jet likeliness for each jet



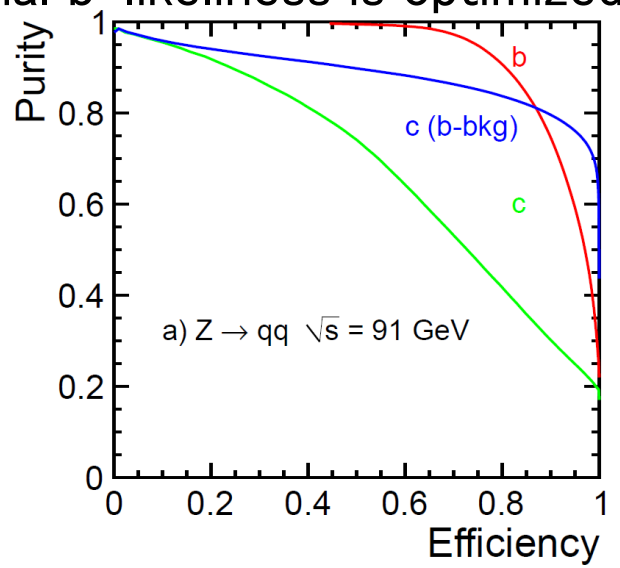


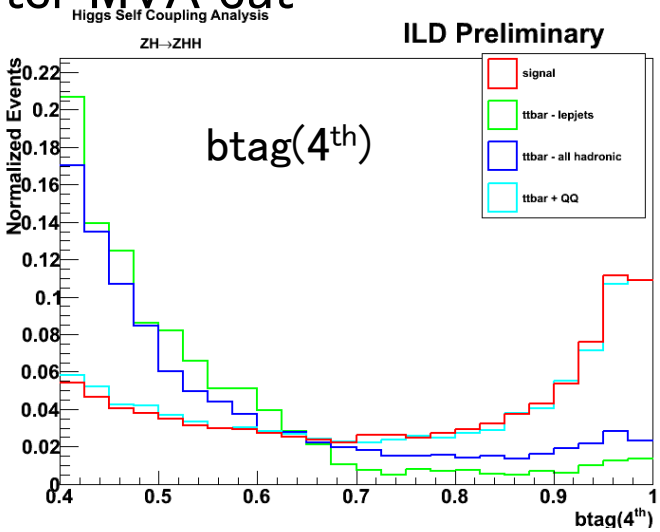


Flavor Tagging

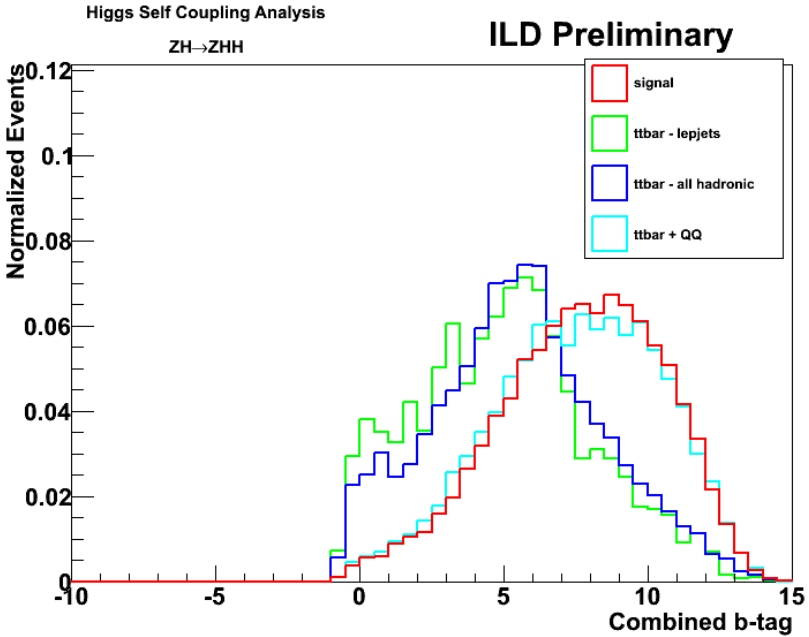
Using LCFIPlus

- b candidate is set >0.4
- Final b-likeliness is optimized after MVA cut





- Introduce combined b-tagging
  - After solving the jet pairing
  - $b(Combined) = \log(\frac{b_1 b_2}{(1-b_1)(1-b_2)})$
  - Use as an input variable for MVA



Background rejection

- Multi Variate Analysis @500GeV
  - Some cuts are implemented before MVA to tighten the input variable space – jet energy, χ^2, visible energy, (Z mass)
  - Background rejection strategy : rejecting small backgrounds first and then rejecting main background
    - Tighten the variable space when rejecting main backgrounds
  - e.g. all hadronic case:

8jets MVA
- ttbar+QQ
- ttbar+Z
- ttbar+H

→

leptonic
- ttbar(lep+jets, dilepton)
- ZZ+H, ZZZ

→

ttbar hadronic
- All hadronic

- Multi Variate Analysis @1TeV
  - Same strategy as the case of 500GeV

ZZ+X MVA
- ZZH
- ZZZ

qq

→

ttbar+X
- ttbar+QQ
- ttbar+Z
- ttbar+H

→

ttbar
- ttbar
- ZWW

Summary and plan

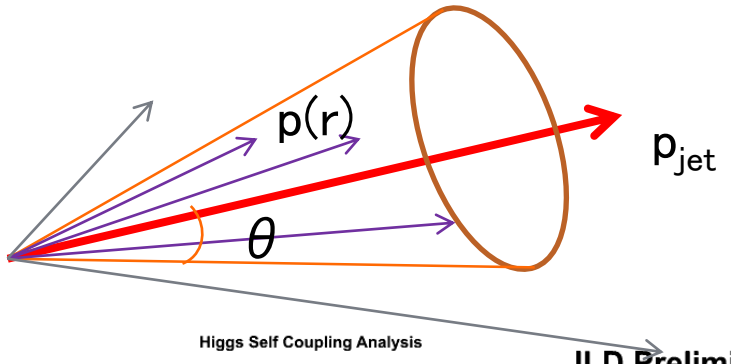
- Higgs self coupling analysis using the events with H→WW* is ongoing.
  - Multi variate analysis to reject the backgrounds
  - Total sensitivity @500GeV is ~1.91 σ
  - Total sensitivity @1TeV is ~2.80 σ

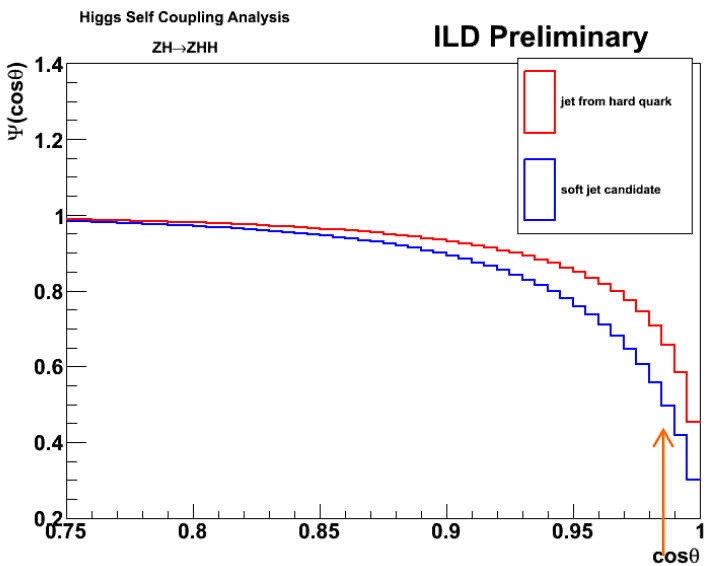
- **Plan:**
  - Start to combine with golden channel and estimate the Higgs self coupling
  - Full simulation @1TeV
  - Optimize b-tagging strategy
    - Forming looser b-tag category
  - Improvement of basic components for the analysis
    - Lepton ID
    - b-tagging
    - Jet energy correction
    - Jet clustering

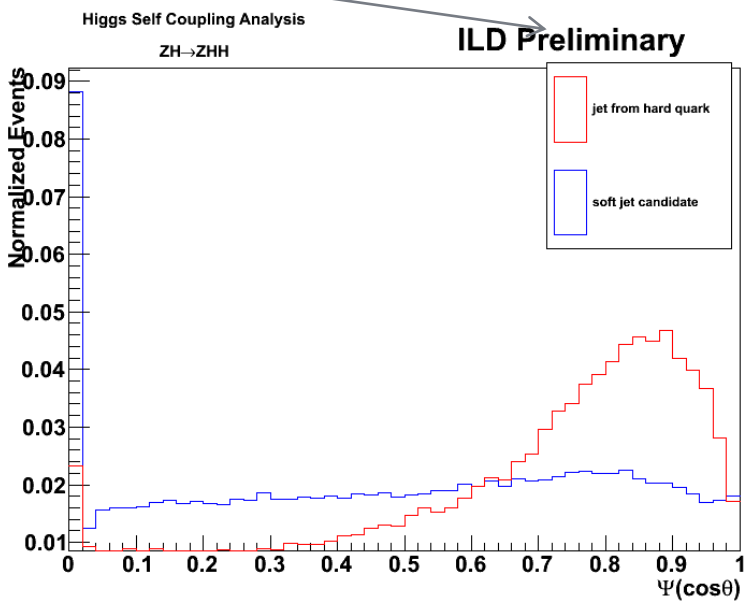
Soft jet finding

- Soft jet finding may be available for the events with extra jets not coming from hard process quarks
  - e.g. 8 jets requirement to ttbar hadronic events(6 jets from hard quarks)
- Traditional jet shape indicates the same tendency as hadron collider analysis

$$\psi(\cos\theta) = \int_1^{\cos\theta} \frac{p(r)}{p_{jet}} dr$$



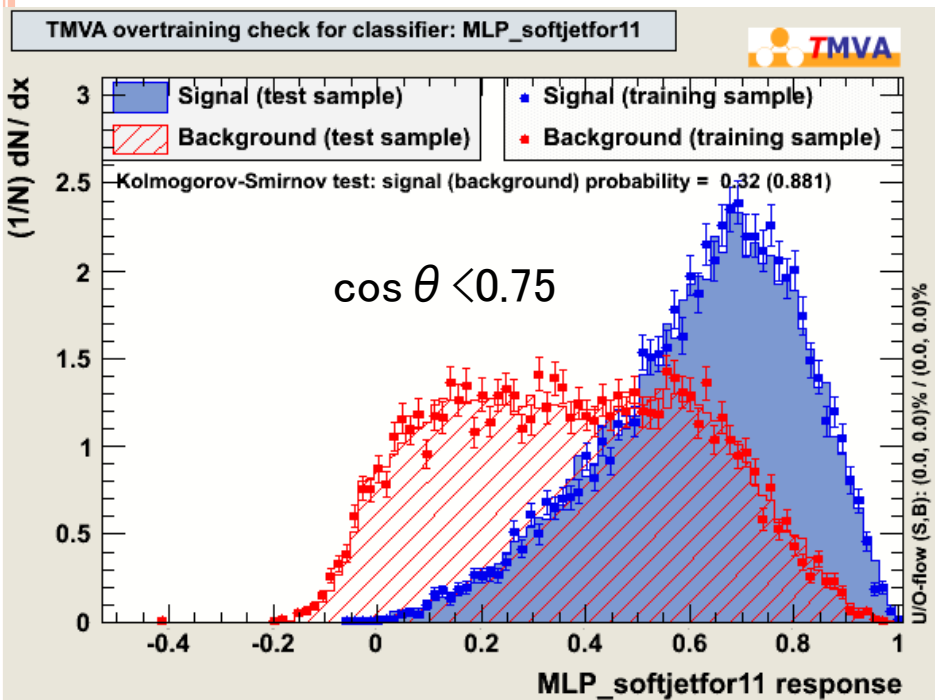


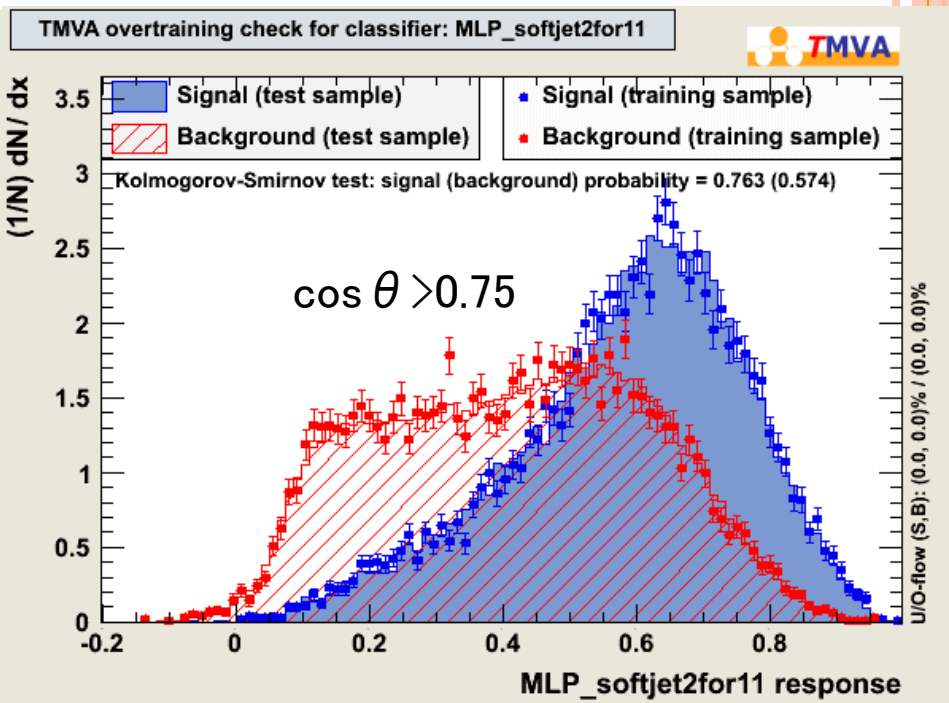


SOFT JET FINDING

- Hard jet likeliness is introduced
  - Using MVA to form it
  - Analysis samples are divided into 2 based on the angle with the nearest jet

  →large shared area for both jets deteriorate the traditional jet shape
- Use the likeliness for the input of background rejection MVA or simple cut of backgrounds





Reduction table

All hadronic

- Final b-tagging: btag(3)>0.92 && btag(4)>0.44
- HH→bbbb contamination is 5.41 events

process	signal	ttbar	tt + QQ	tt+Z	tt + H	ZZ + H	ZZZ
expected	354.00	1.16×10^6	1660.00	3307.00	280.00	1540.00	3660.00
preselection	49.47	2462.09	79.11	76.25	38.32	87.22	70.72
Jet energy	47.92	1970.58	77.62	74.98	37.96	72.88	57.28
$\chi 2$	44.32	1353.38	64.57	62.41	34.02	61.60	48.16
Visible energy	44.23	1326.19	64.31	62.00	33.92	61.18	47.90
NN for 8 jets	36.51	1011.92	36.37	34.37	16.38	51.59	47.90
NN for ttbar	20.53 (9.85)	302.59	26.44	25.17	13.07	21.71	9.00
b-tagging	14.92 (5.41)	87.54	17.54	16.42	9.13	16.10	6.03