



九州大学
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HIGGS SELF COUPLING ANALYSIS USING THE EVENTS CONTAINING $H \rightarrow WW^*$ DECAY

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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

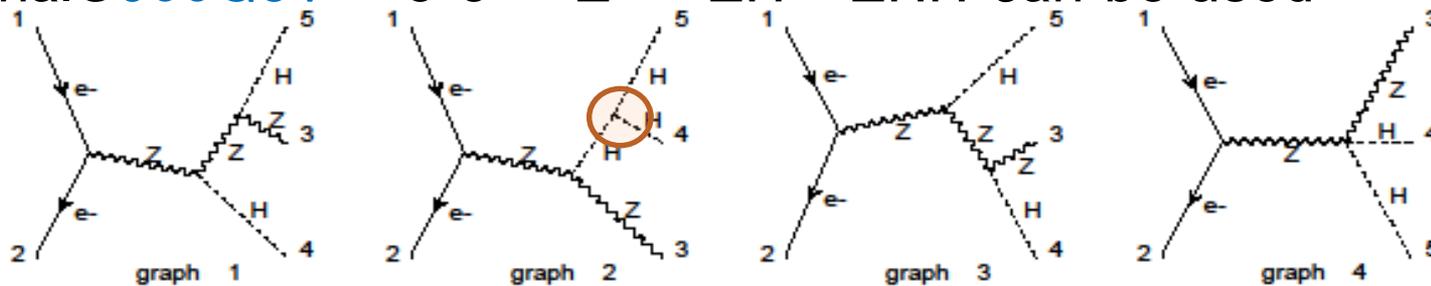
→ difficult to measure

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

- 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

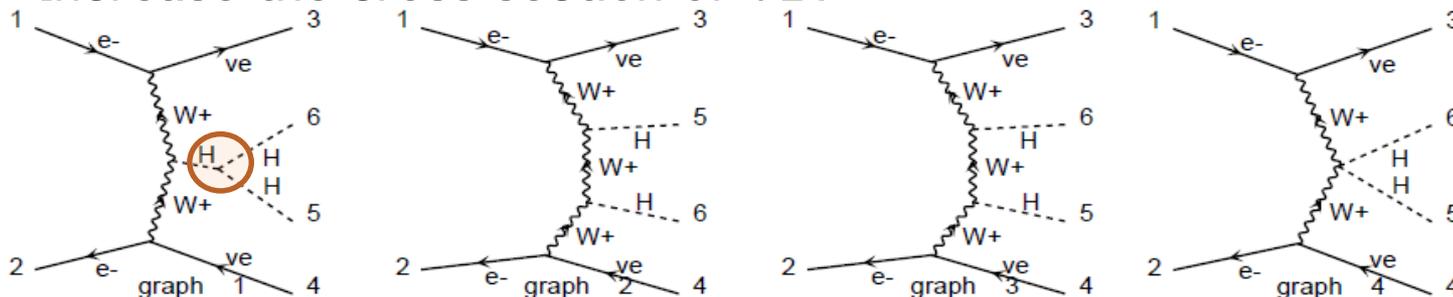
Signal@500GeV - $e^+e^- \rightarrow Z^* \rightarrow ZH \rightarrow ZHH$ can be used



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

Signal@1TeV - VBF $e^+e^- \rightarrow \nu \nu HH$ channel is opened

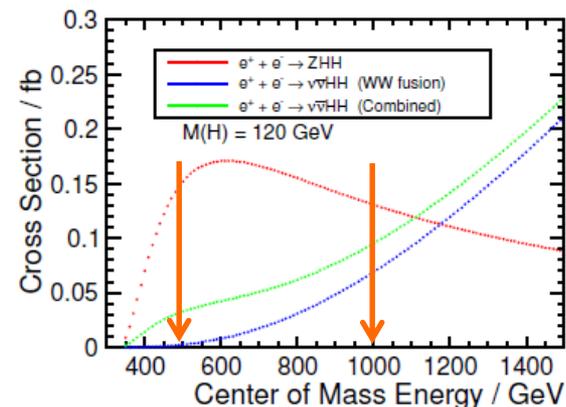
- Increase the cross section of VBF



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

Higgs decay modes:

- $HH \rightarrow (bb)(bb)$: golden channel thanks to b-tag
- $HH \rightarrow (bb)(WW)$: 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 <ul style="list-style-type: none"> • ZZ + H • ZZZ 	Small cross section b-jet rich in the final states	Kinematics topology Difference of the final states

S/B \sim 1/3000@500GeV, 1/1000@1TeV

○ Simulation

	500GeV	1TeV
Polarization (e,p)	(-0.8,+0.3)	(-0.8,+0.2)
$m_H(\text{GeV}/c^2)$	125	125
simulator	Full(DBD)	Full(DBD)

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

COMPONENTS FOR BETTER RESULTS

- 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

TRYING KINEMATIC FITTER@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 $-2\log(\text{likelihood})$) minimization
- $ZHH \rightarrow (bb)(bb)(WW^*) \rightarrow (bb)(bb)(l\nu jj)$ kinematic fitter

- Constraints:

$$m(bb) = m_Z$$

$$\text{Max}(m(l\nu), m(jj)) = m_W$$

$$m(bb) = m(l\nu jj)$$

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

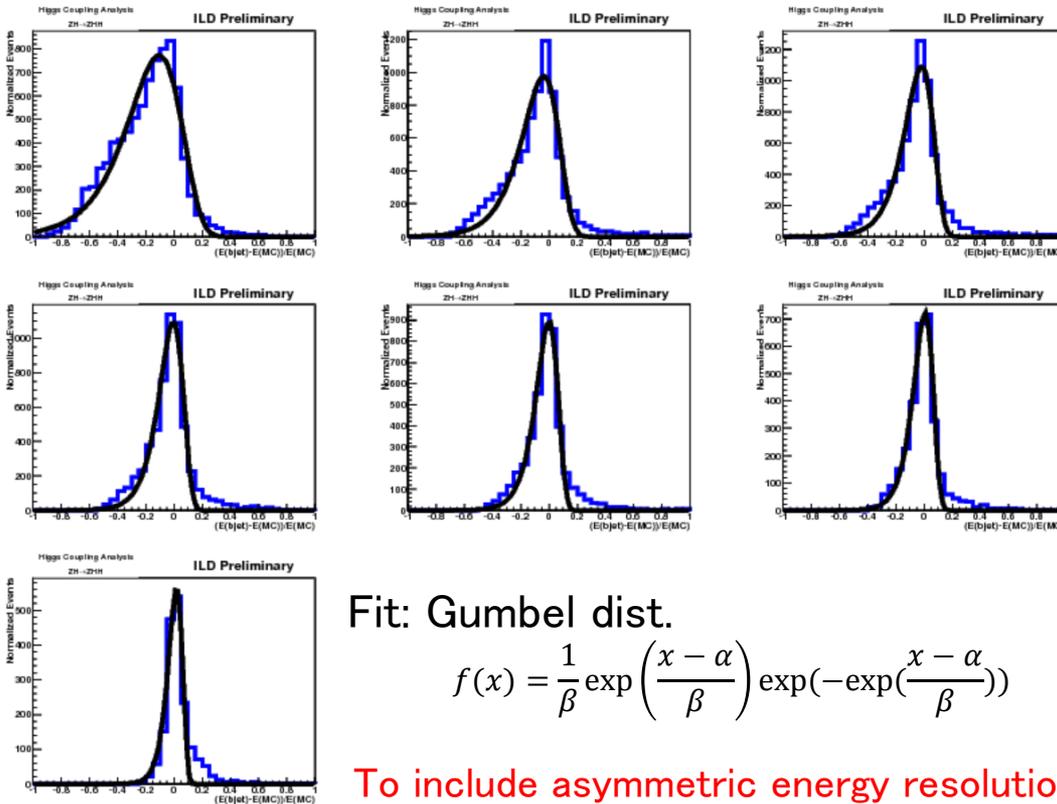
$$\vec{p}_H + \vec{p}_Z + \vec{p}_{jj} + \vec{p}_{l\nu} = \vec{0}$$

$$|\vec{p}_\nu| = E_\nu$$

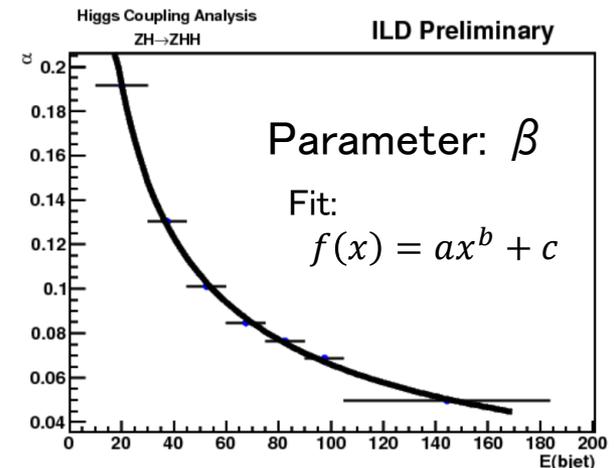
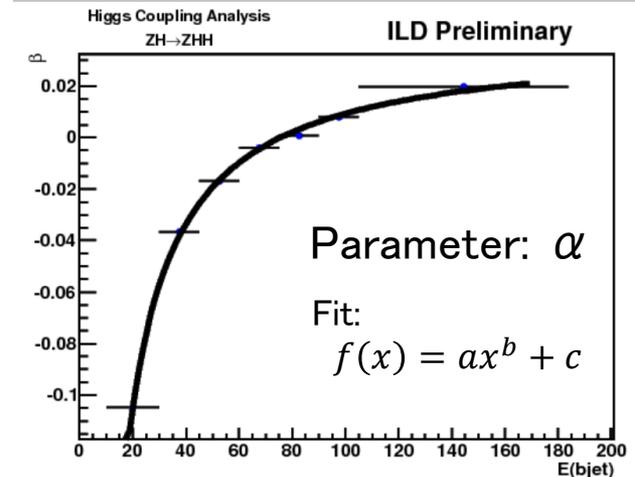
JET ENERGY RESOLUTION

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.) b_{jet} energy resolution

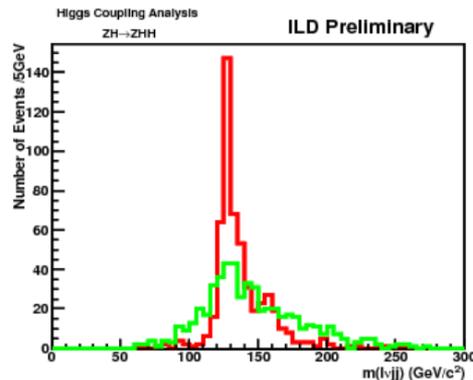
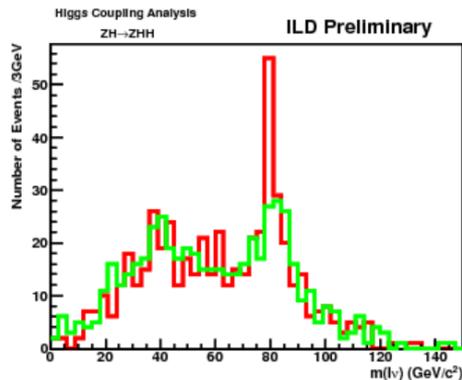
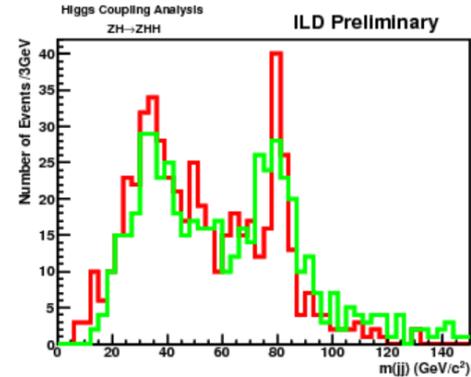
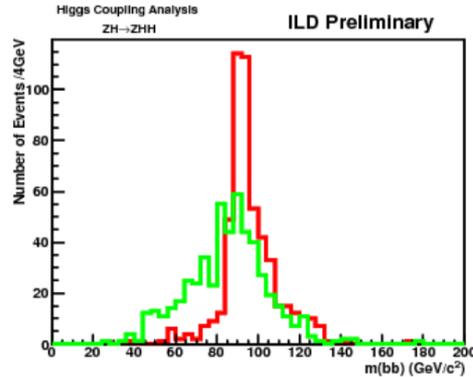
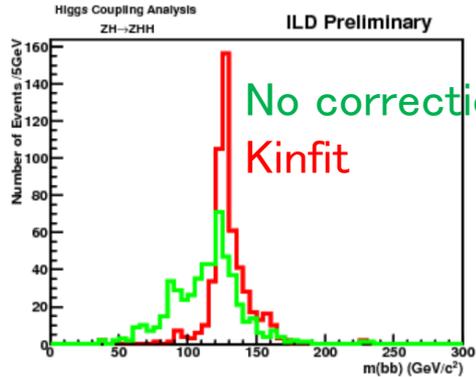


To include asymmetric energy resolution



PERFORMANCE CHECK

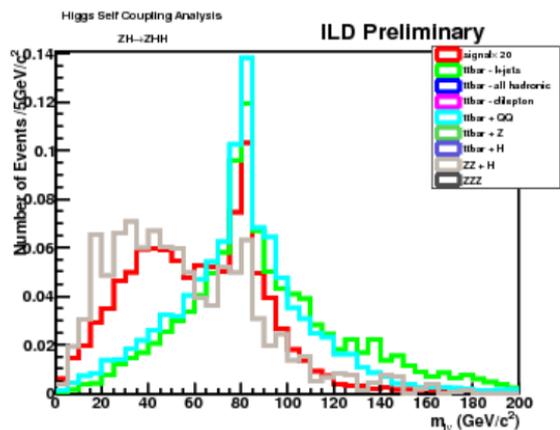
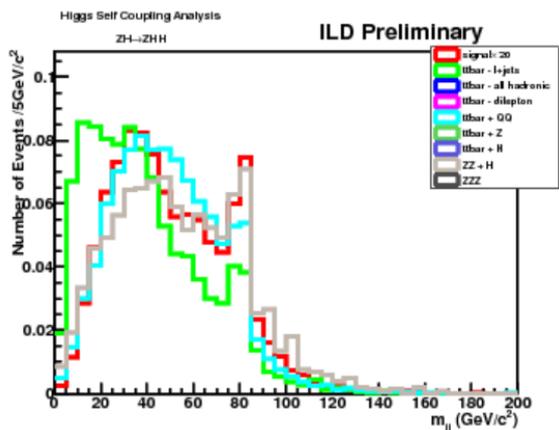
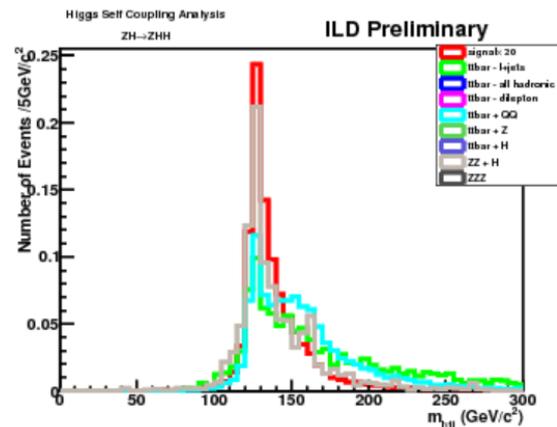
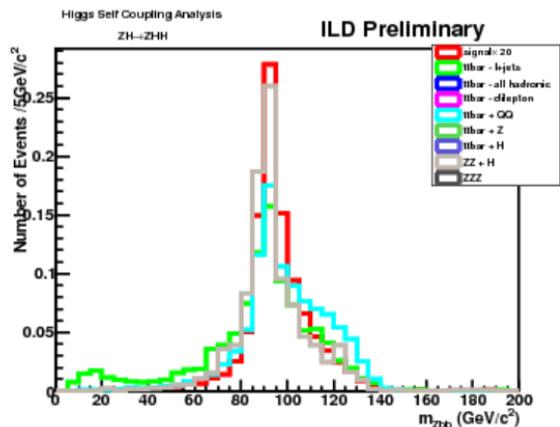
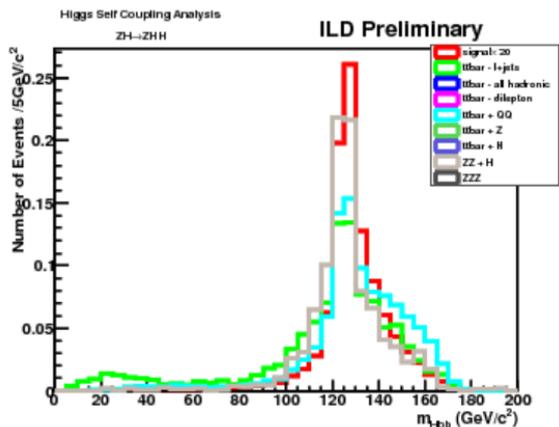
- Higgs mass($H \rightarrow bb$) & Z mass distribution
 - Mass resolution is going better! \rightarrow promising



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

COMPARISON BETWEEN SIGNAL AND BACKGROUNDS

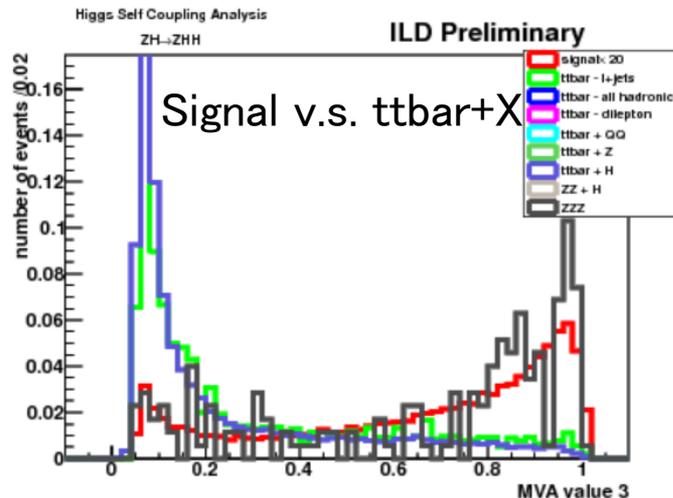
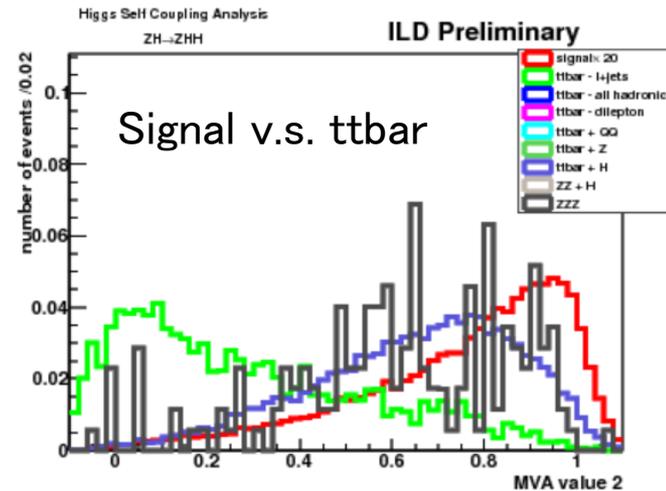
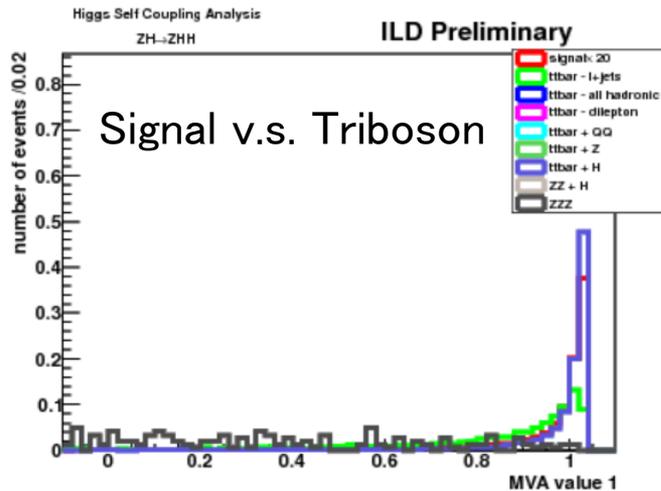
- Higgs mass($H \rightarrow bb$) & Z mass distribution
 - How are mass distributions of backgrounds?
 - ZZH background is hard to reject?
 - Top related backgrounds will be separated well



Signal
 ttbar lep+jets
 ttbar+g
 ZZ+H

BACKGROUND REJECTION

- Same way as former results – include kinfit results as input variables
 - Phase space is quite different between backgrounds, so train MVA for each background component



Signal
ttbar(l+jets)
ttbar + H
ZZH

PRELIMINARY RESULT@500GeV

- Higgs-strahlung process, $ZHH \rightarrow (bb)(bb)(WW) \rightarrow (bb)(bb)(l \nu jj)$
- 4 b-tagging, tight
- Calculate the significance, $\frac{s}{\sqrt{s+b}}$
- $L=2ab^{-1}$

Conference	Category	Signal	Background	Significance
AWLC14	Lepton+ 6jets	2.07	20.65	0.41 σ
ALCW15	Lepton+ 6jets	1.72	14.55	0.43 σ
Improvement				$\sim 4.7\%$

- Kinematic fitter only gives $\sim 5\%$ improvement...
 - Need to investigate more

TRYING KINEMATIC FITTER@1TeV

- In 1TeV case, VBF process is the promising process to measure Self-coupling well

- Weighting factor becomes small for VBF process against ZHH process

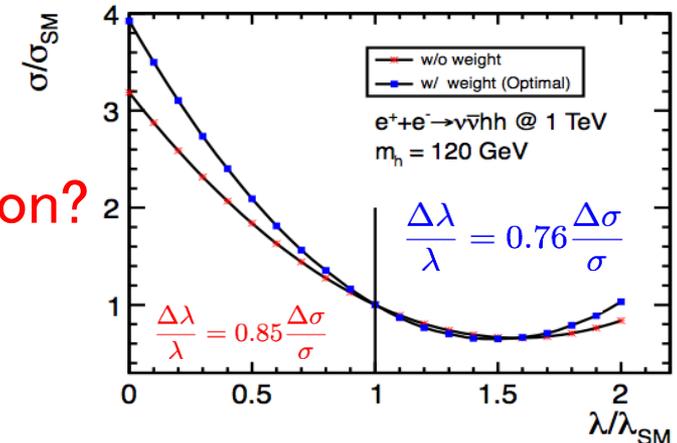
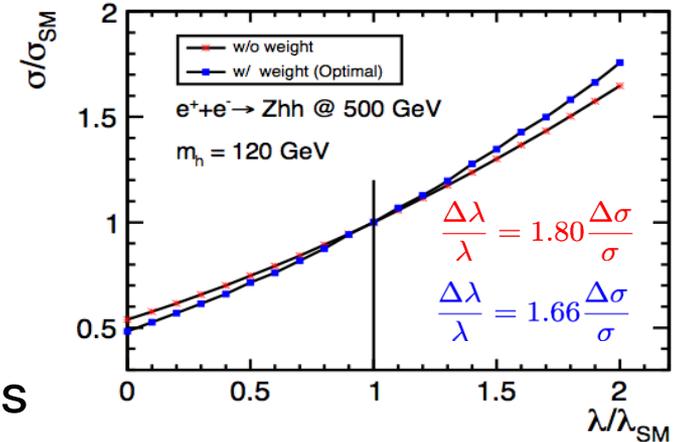
- Process of $e^+e^- \rightarrow \nu \nu HH$

- Disadvantage of $HH \rightarrow (bb)(WW^*)$: b-tagging
- b-tagging available is only 2!
- $t\bar{t}$ backgrounds can't be suppressed even if using b-tagging

- So, background rejection using kinematics is the key to good results

- Kinematic fitter helps background rejection?

J. Tian, LC-REP-2013-003



KINEMATIC FITTER@ 1TeV

○ Construct $\nu \nu HH \rightarrow \nu \nu (bb)(WW) \rightarrow \nu \nu (bb)(jjj)$

- Constraints: $m(H1)=m(H2)$

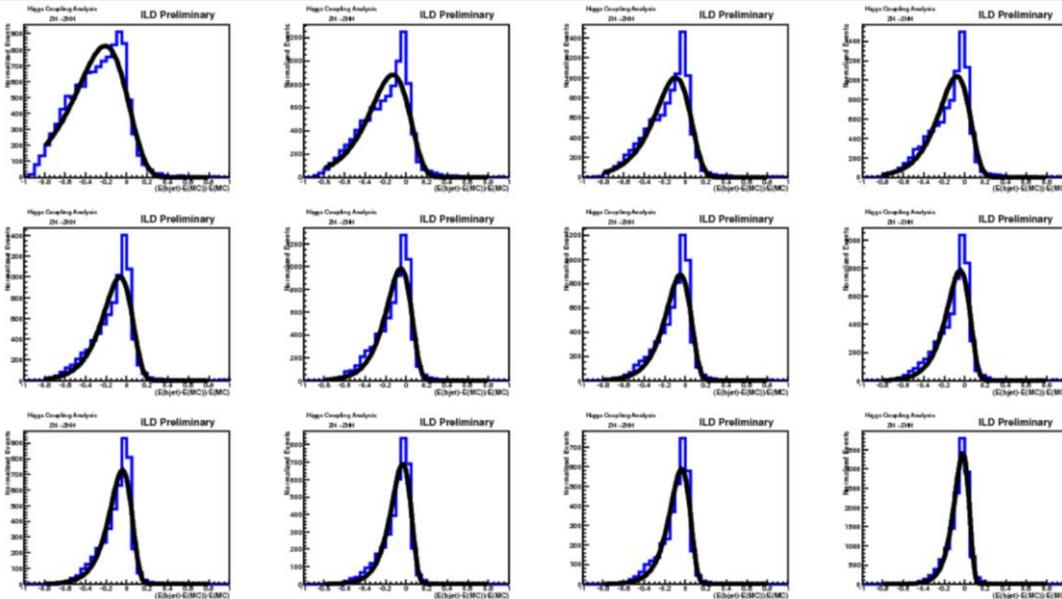
$$\text{Max}(m(jj), m(jj)) = m_W$$

$$\vec{p} = \vec{0}, \text{ include missing}$$

$$\sum E = 1\text{TeV}, \text{ include missing}$$

○ Jet energy resolution effect is included to kinematic fitter

- Same way as @500GeV
- Energy dependence of jet energy resolution itself is considered



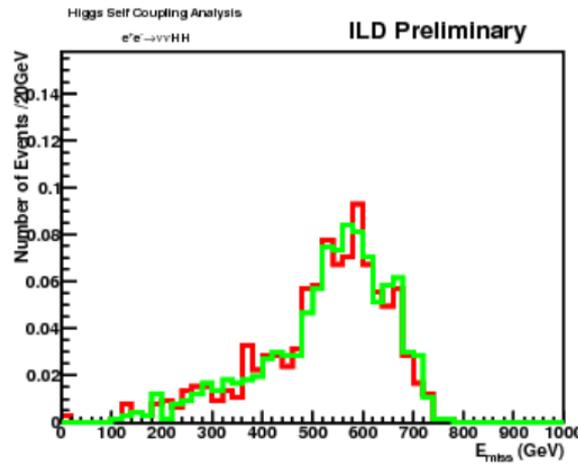
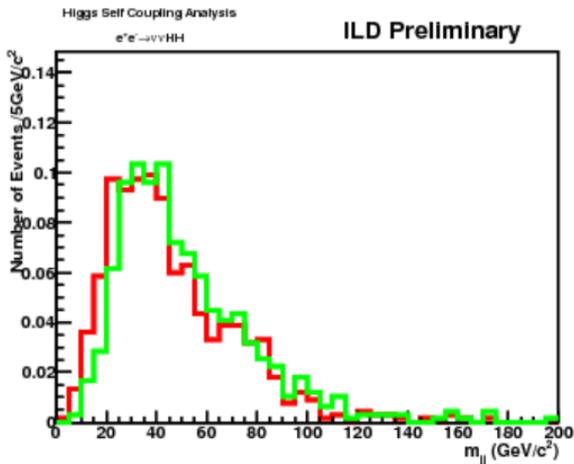
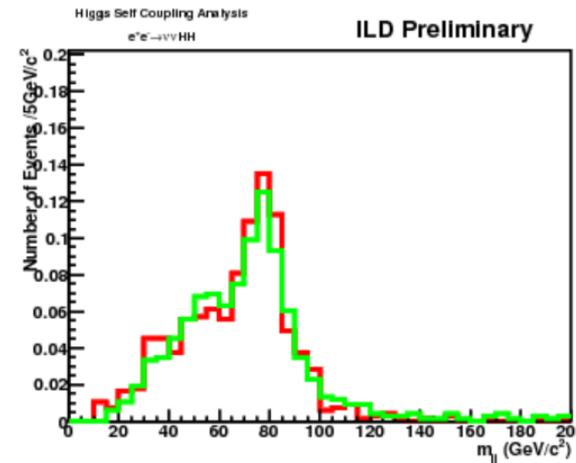
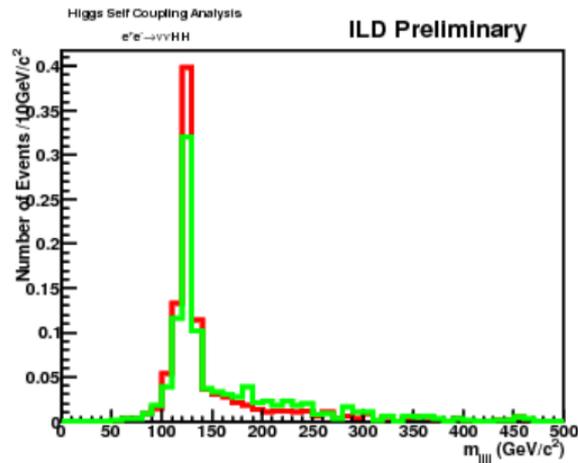
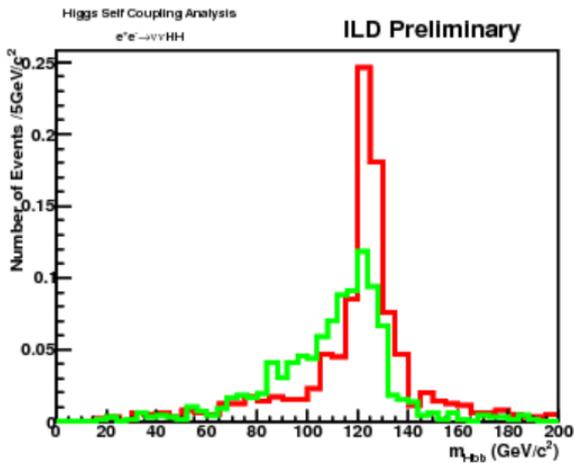
e.g.) bjet jet energy resolution

Fit: Gumbel dist.

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

PERFORMANCE CHECK

- Higgs mass($H \rightarrow bb$) & Z mass distribution
 - Mass resolution is going better! \rightarrow promising

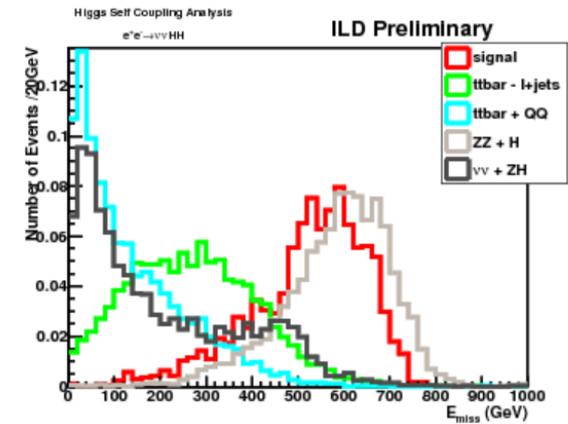
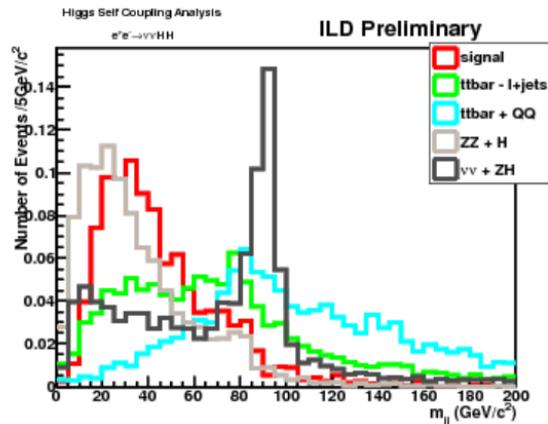
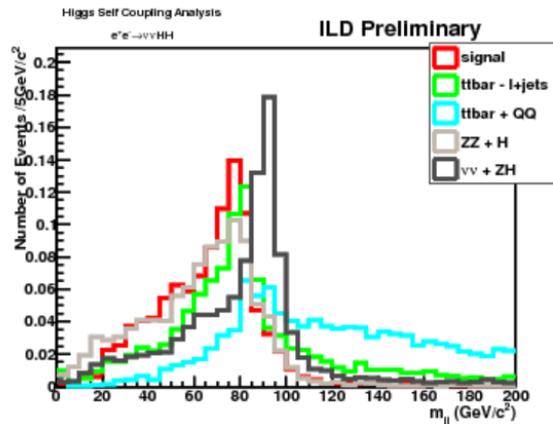
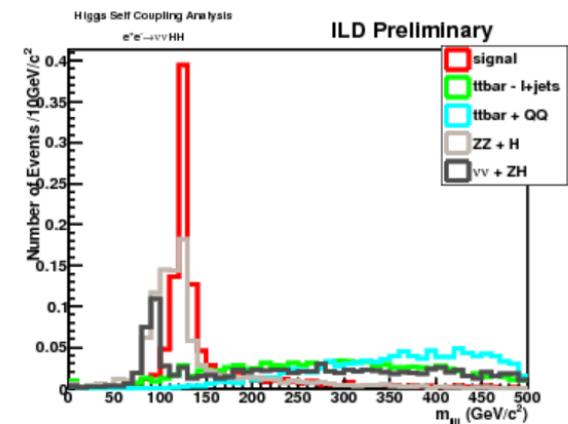
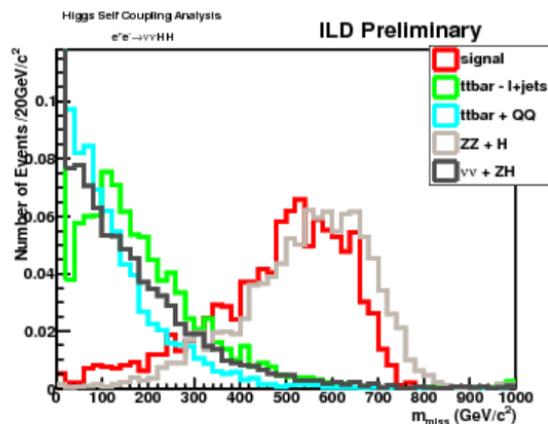
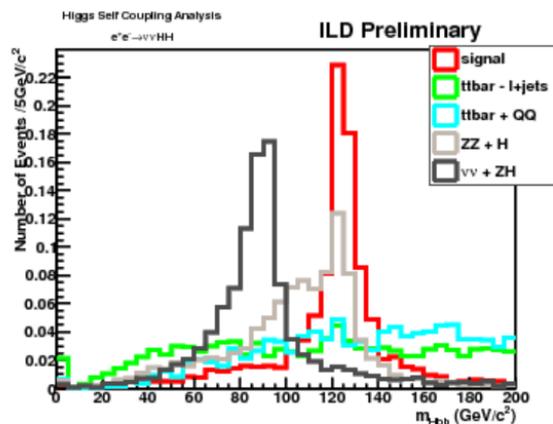


No correction
Kinfit

COMPARISON BETWEEN SIGNAL AND BACKGROUNDS

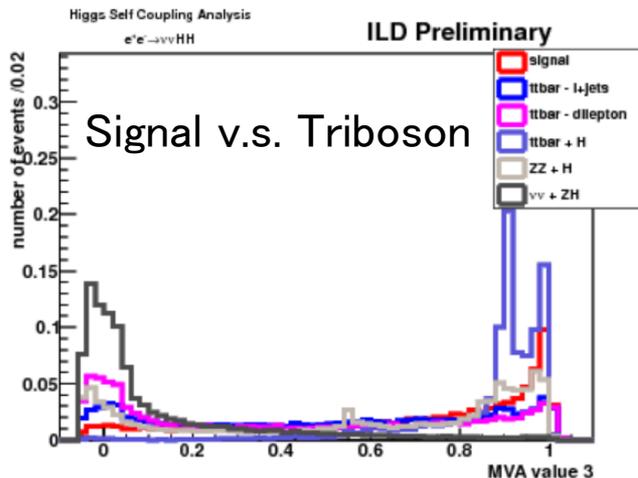
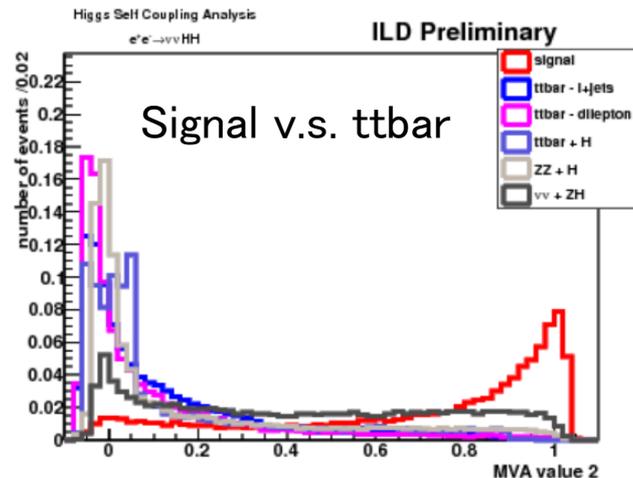
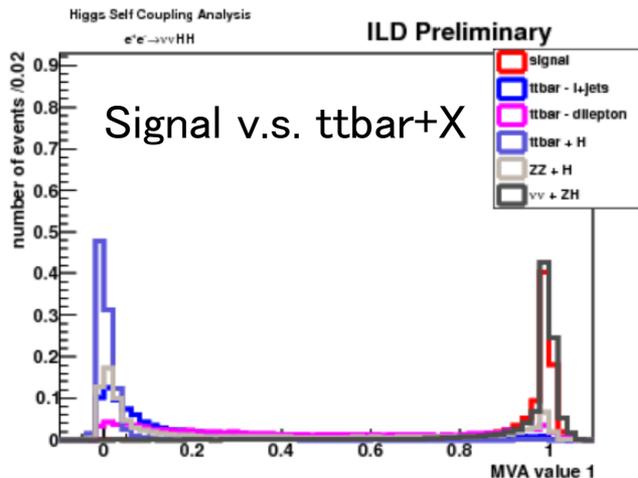
Each mass & missing energy distribution

- How are mass distributions of backgrounds?
- ZZH background is hard to reject?
- Top related backgrounds will be separated well
- $m(H1)=m(H2)$ constraint will be powerful in this case!



BACKGROUND REJECTION

- Same way as former results – include kinfit results as input variables
 - Phase space is quite different between backgrounds, so train MVA for each background component



Signal
ttbar(lep+jets)
ttbar(dilepton)
ttbar + H
ννZH
ZZH

PRELIMINARY RESULT@1TeV

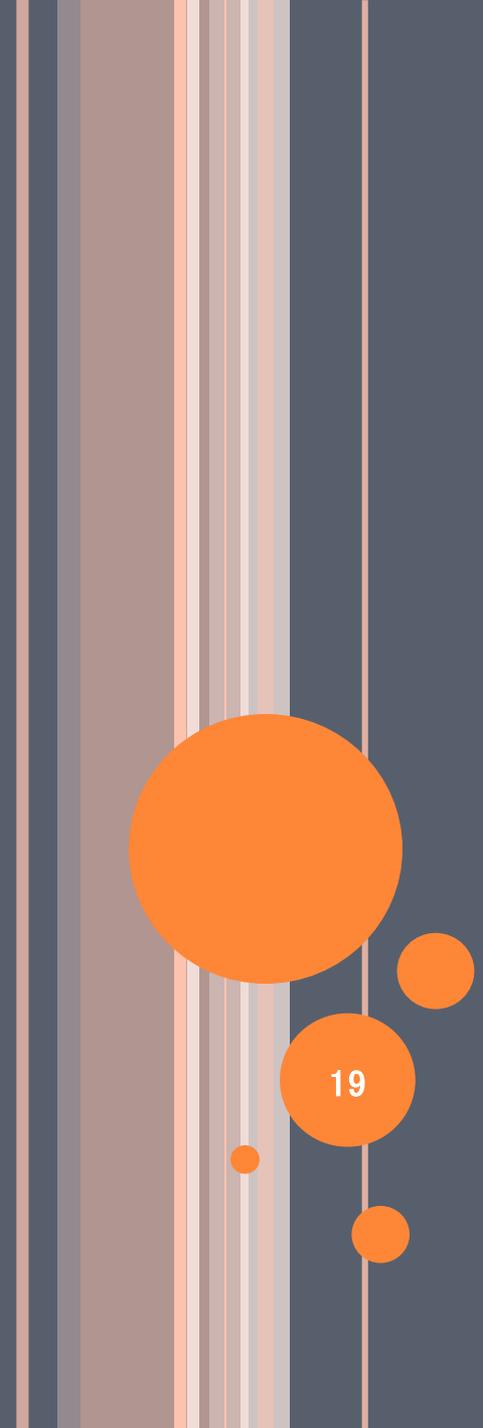
- VBF process, $\nu \nu HH \rightarrow \nu \nu (bb)(WW) \rightarrow \nu \nu (bb)(jjjj)$
- 2 b-tagging, tight
- Calculate the significance, $\frac{s}{\sqrt{s+b}}$
- $L=2ab^{-1}$

Conference	Z decay	Signal	Background	Significance
LCWS13(Fast Sim.)	No Z, $\nu \nu HH$	6.90	8.24	1.77 σ
ALCW15	No Z, $\nu \nu HH$	7.23	6.44	1.96 σ
Improvement				10.2%

- Thanks to Kinematic fitter, $\sim 10\%$ improvement is obtained

SUMMARY AND PLAN

- Higgs self coupling analysis using the events with $H \rightarrow WW^*$ is ongoing.
 - Kinematic fitting will be a good tool for mass resolution improvement
 - @1TeV, 10% improvement can be obtained thanks to Kinematic Fitter
 - @500GeV, kinematic fitter provides improvement, but only 5%
- **Plan:**
 - Using Kinematic fitter to ZHH all hadronic events
 - $\nu \nu HH \rightarrow \nu \nu (bb)(WW) \rightarrow \nu \nu (bb)(l \nu jj)$ process analysis
 - Basic analysis components need improvement
 - Finally, incorporate all the improvements and update the self-coupling result!



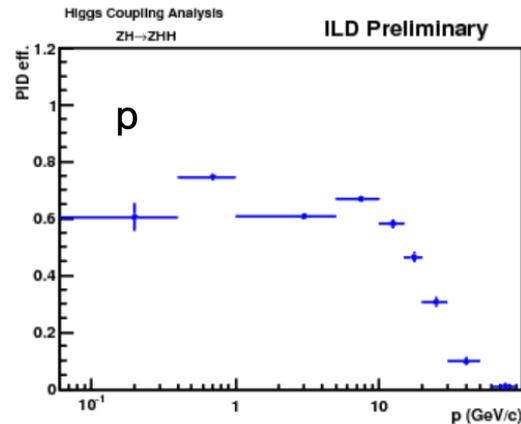
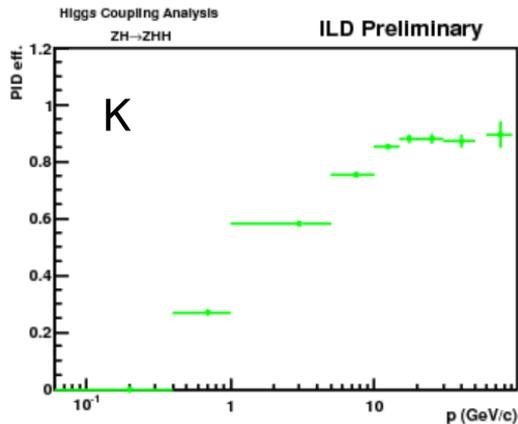
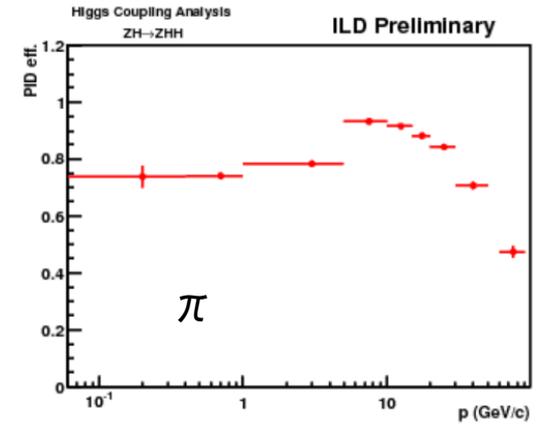
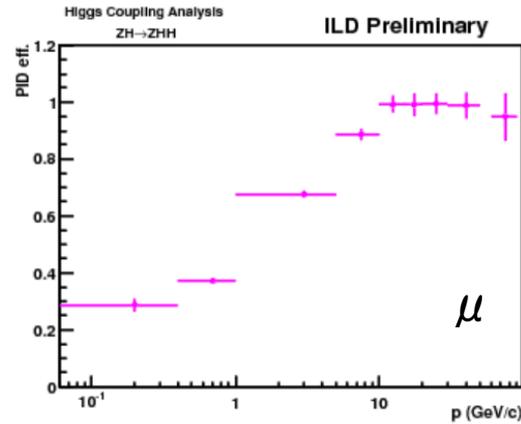
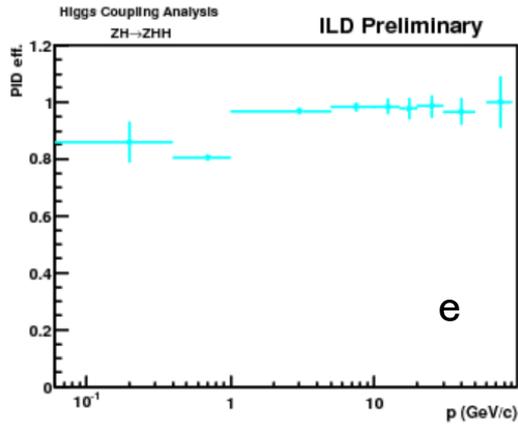
SOME EXTRAS FOR OTHER SESSIONS

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LOOK MORE

○ Momentum Dependence of Particle ID efficiency

- Momentum ranges where PID is good/bad



- Electron ID is good
- PID efficiency is $>60\%$ @ $1\text{GeV}/c \sim 20\text{GeV}/c$
- Low momentum μ / π separation is difficult
- Too low momentum PID is not effective (tracking is good?)

VERTEX CLASSIFICATION

Can Particle ID be used for flavor tagging improvement?

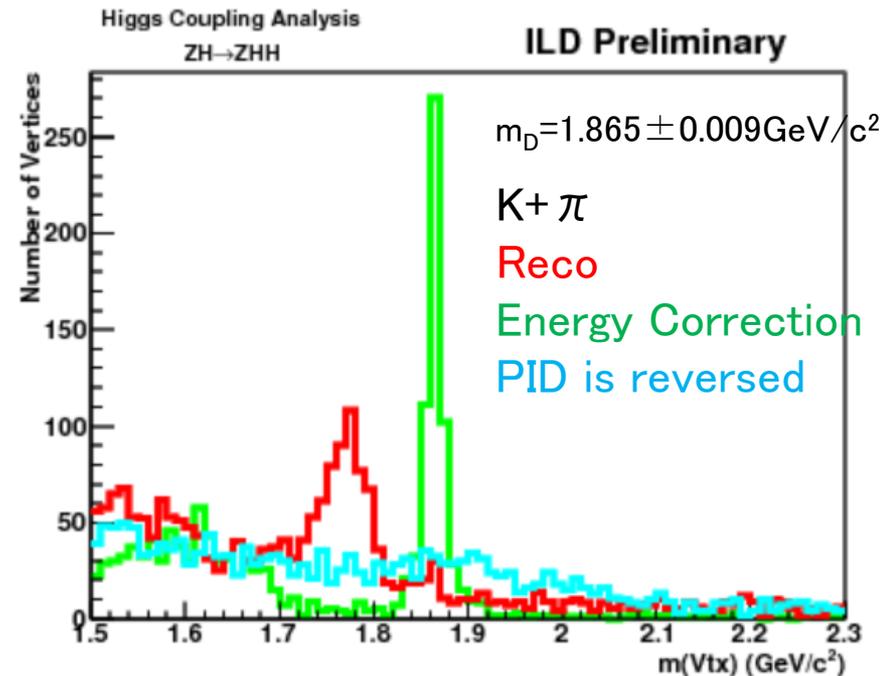
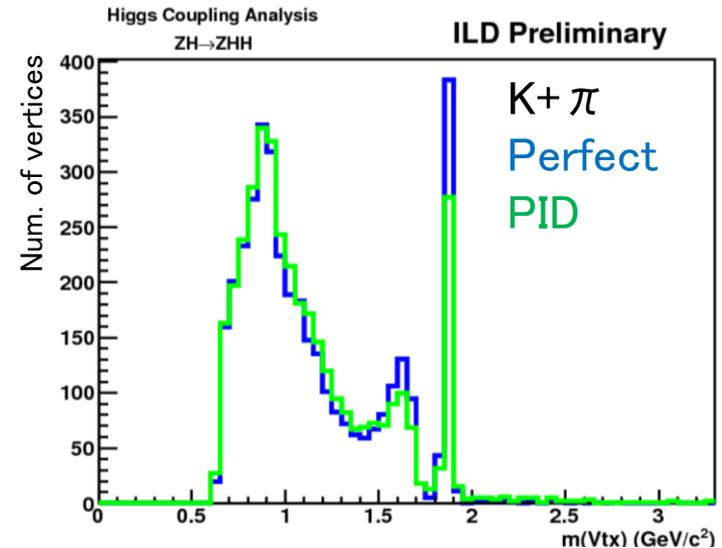
- Checking vertex mass distribution
- Vertex is from LCFIPlus
- How much effect on vertex mass?

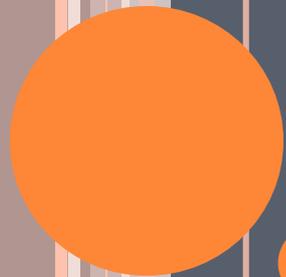
Check D meson reconstruction

- Track energy correction using PID
- How much D meson mass is close to PDG value($1.869 \pm 0.0001 \text{ GeV}/c^2$)?
- How much does wrong PID destroy D meson mass?

$m_D = 1.865 \pm 3\sigma$ is defined as D meson mass range

status	Inside	outside
PID Correct(num. of vtx)	550	(6940)
PID reversed(num. of vtx)	83	77
Inversed PID is near nominal D mass	22	77





BACKUPS

ANALYSIS STRATEGY FOR $HH \rightarrow (BB)(WW)$

- Classify the events with Z and W decays:

@500GeV	$WW \rightarrow (qq)(qq)$	$WW \rightarrow (qq)(l \nu)$	@1TeV	$WW \rightarrow (qq)(qq)$	$WW \rightarrow (qq)(l \nu)$
$Z \rightarrow bb$	8jets	Lepton+6jets	$Z \rightarrow bb$	8jets	Lepton+6jets
$Z \rightarrow cc$	8jets	Lepton+6jets	$Z \rightarrow ll$	Dilepton+6jets	N/A
$Z \rightarrow ll$	Dilepton+6jets	Trilepton+4jets	$\nu \nu HH$	6jets (+missing)	N/A

- Z decays into heavy flavor pair or lepton pair mainly**

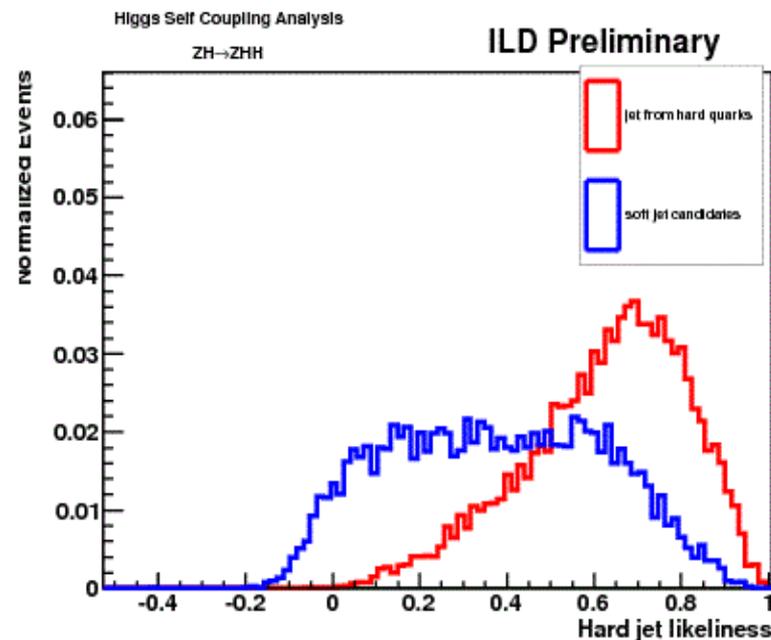
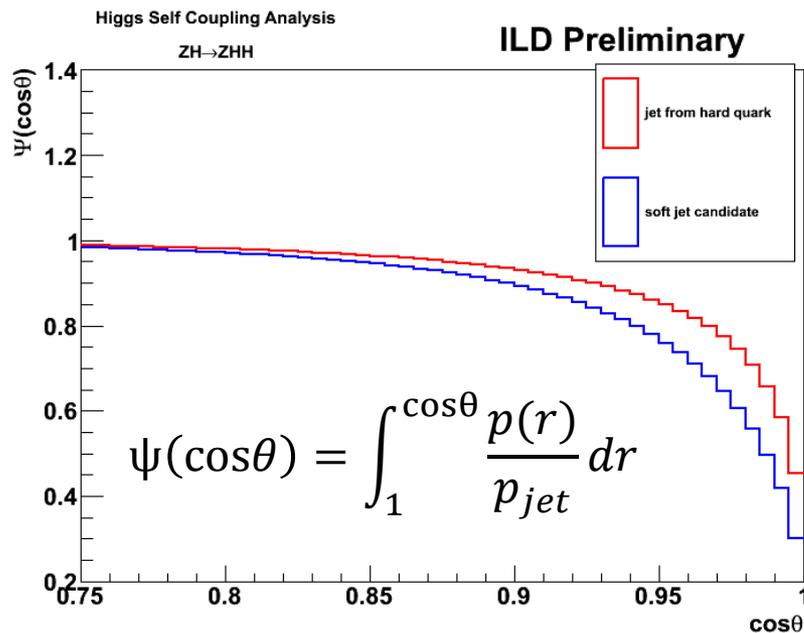
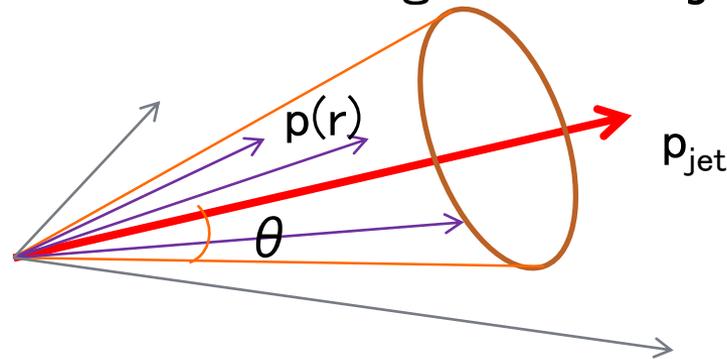
- Need flavor tagger or clean Z mass distribution to reject huge backgrounds

- Number of b jet candidates in the event and number of leptons can form exclusive samples**

- Number of b-tagging available: up to 4
 - Basically, 2 or 4 b-tagged jets events can be used
 - c-tagging is also available
- Number of leptons: from 0 to 3

SOFT JET FINDING

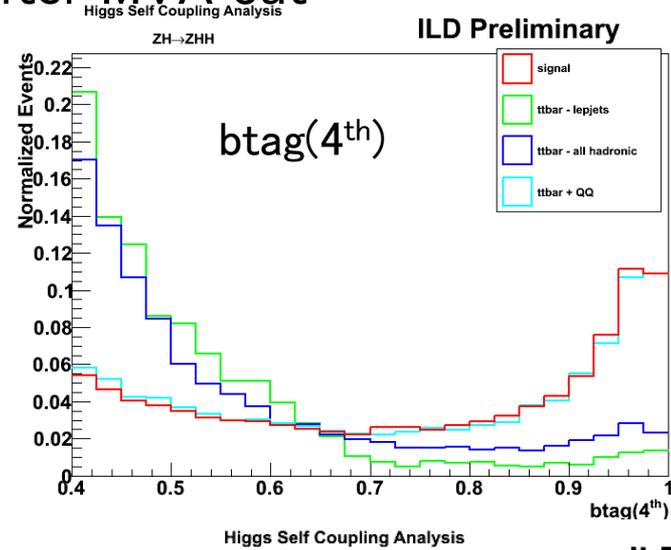
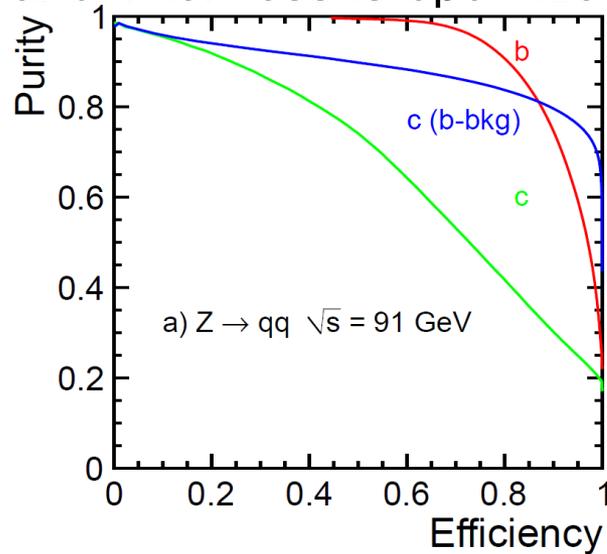
- Tracks in the gluon jets spread wider than those in quark jets (e.g. analyses on hadron collider)
 - Traditional jet shape can be a good estimator
- Using Multivariate Analysis and estimating the hard jet likeliness for each jet



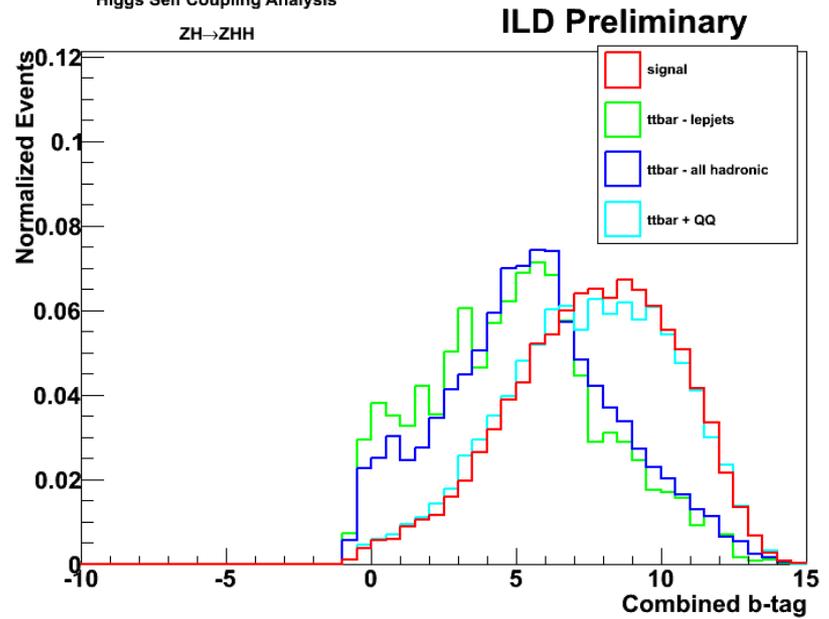
FLAVOR TAGGING

Using LCFIPlus

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



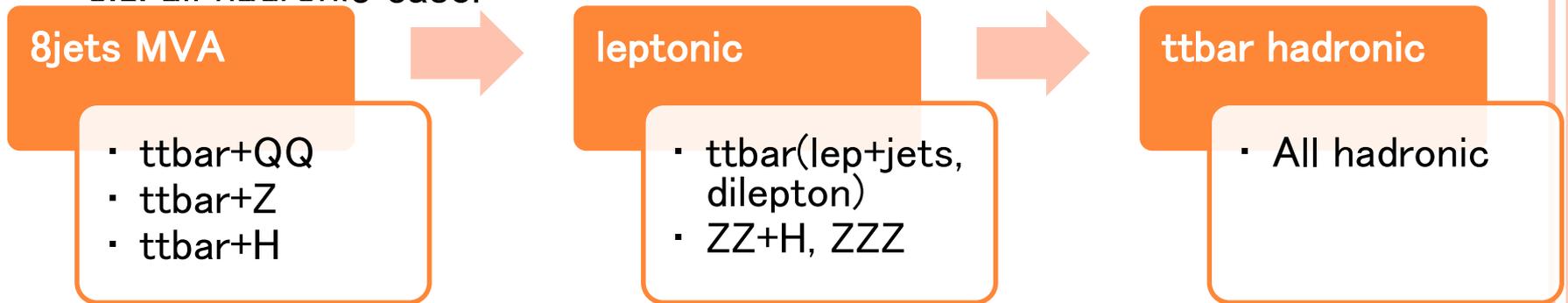
- Introduce combined b-tagging
 - After solving the jet pairing
 - $b(\text{Combined}) = \log\left(\frac{b_1 b_2}{(1-b_1)(1-b_2)}\right)$
 - Use as an input variable for MVA



BACKGROUND REJECTION

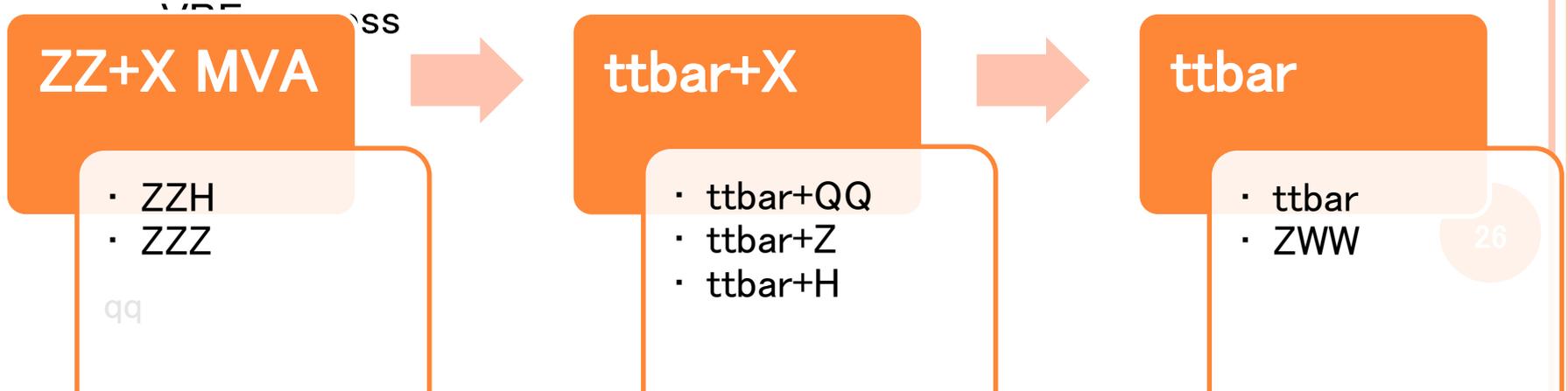
Multi Variate Analysis @500GeV

- 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:



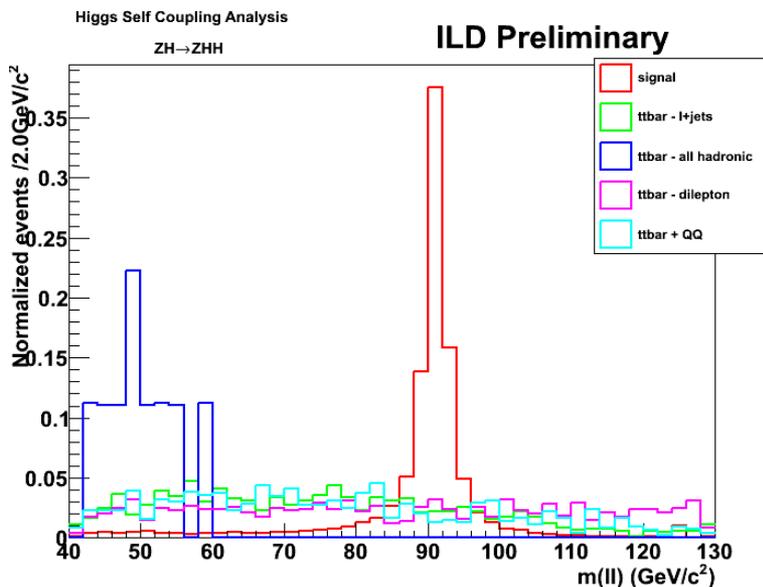
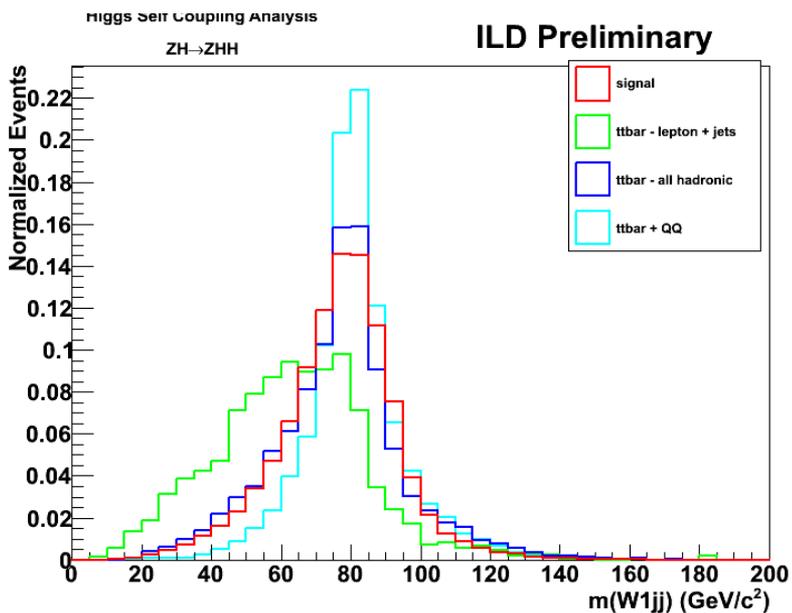
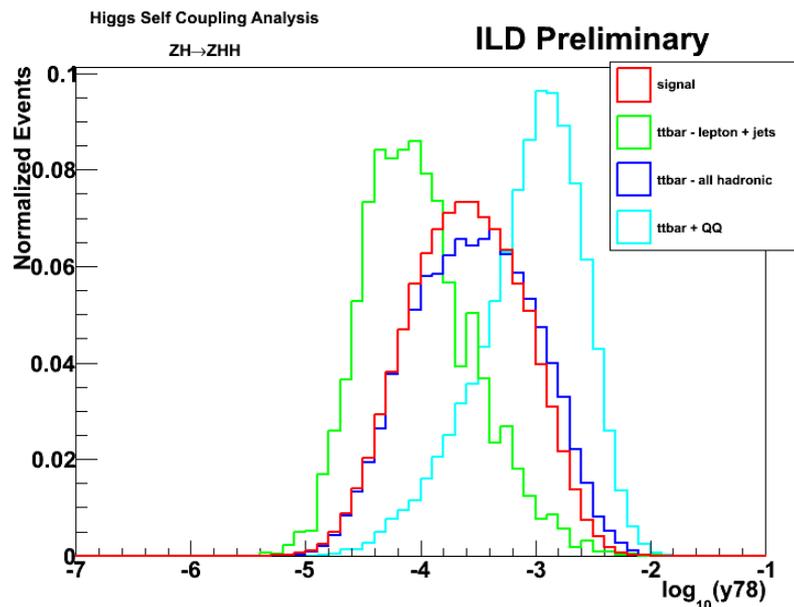
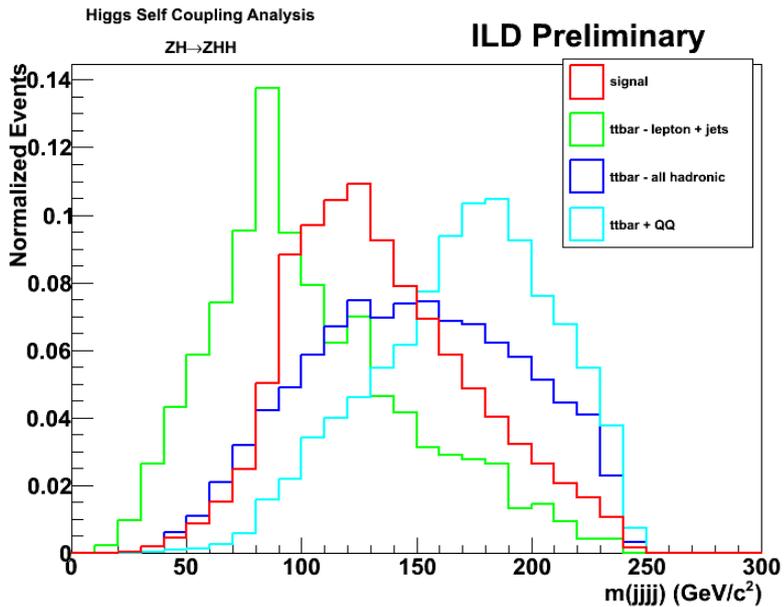
Multi Variate Analysis @1TeV

- Same strategy as the case of 500GeV



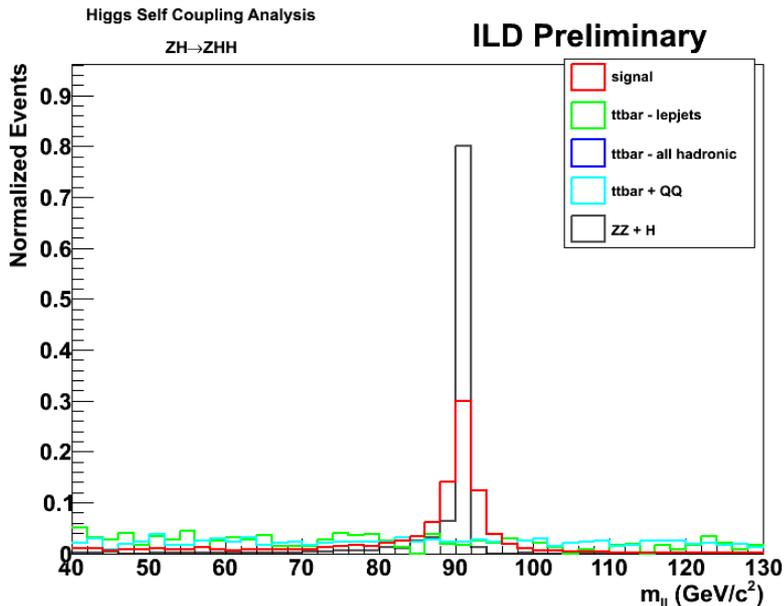
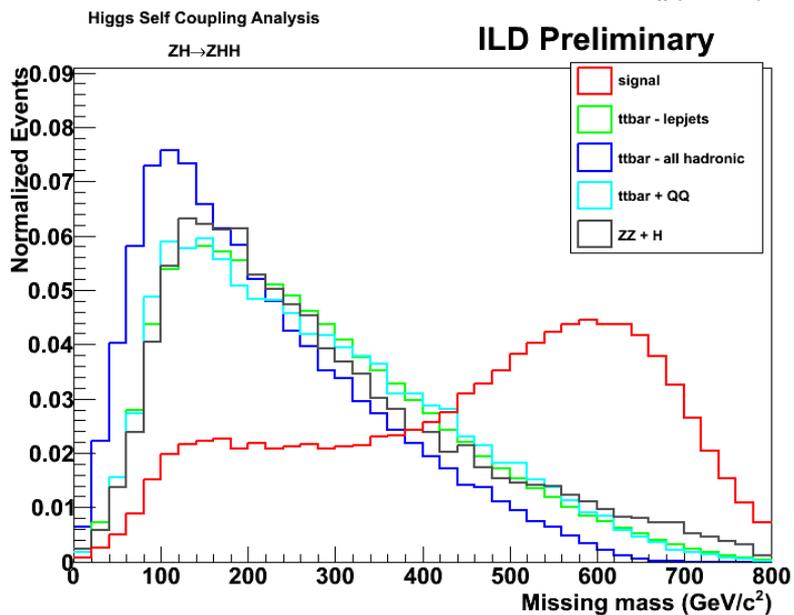
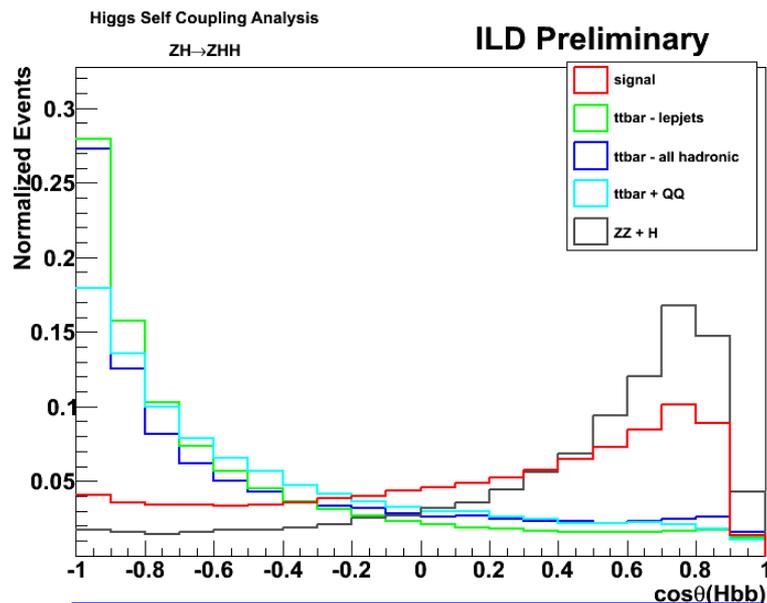
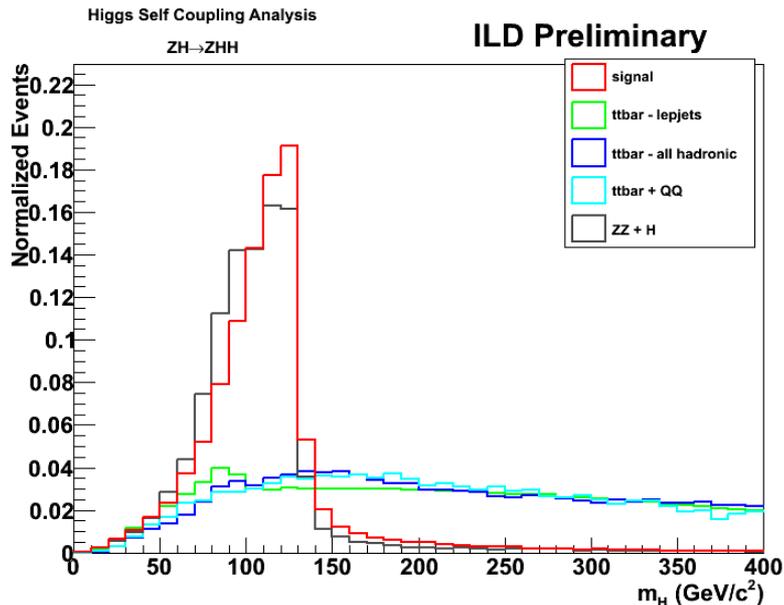
SOME KINEMATIC VARIABLES USED FOR MVA

Very powerful variable @500GeV: $m(jjjj)$, $m(l \nu jj)$



SOME KINEMATIC VARIABLES USED FOR MVA

Very powerful variable @1TeV: m_H , $\cos \theta$ (Hbb)



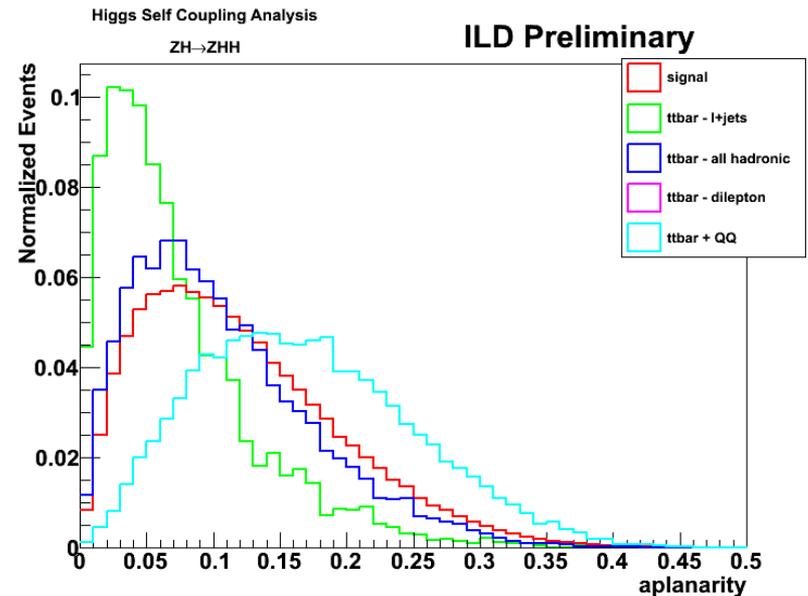
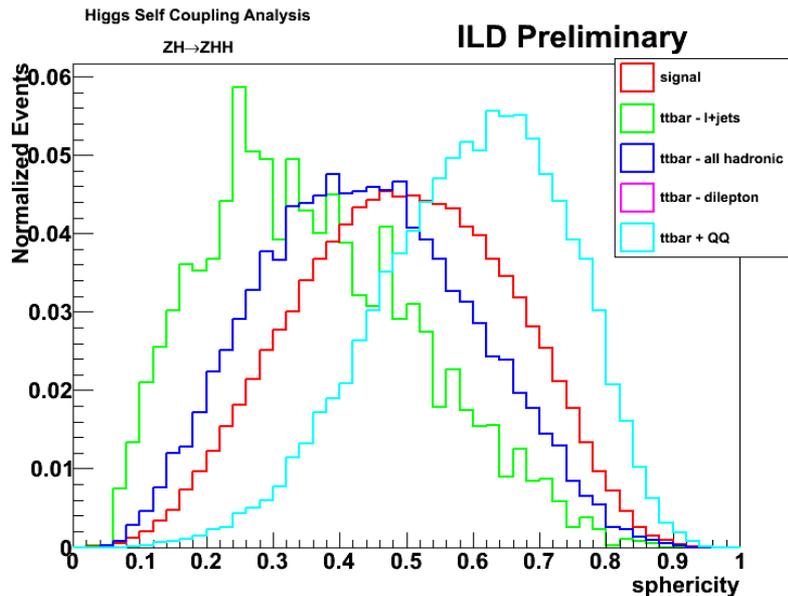
NON-SIMPLE VARIABLES USED FOR MVA

○ Sphericity and aplanarity

- Eigenvalue combinations of sphericity tensor:

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\mathbf{p}_i|^2}, \quad \text{eigenvalues: } \lambda_1 > \lambda_2 > \lambda_3$$

- Sphericity: $S = \frac{3}{2}(\lambda_2 + \lambda_3)$
- Aplanarity: $A = \frac{3}{2}\lambda_3$
- Indicates whether the event is 2-jets like or isotropic

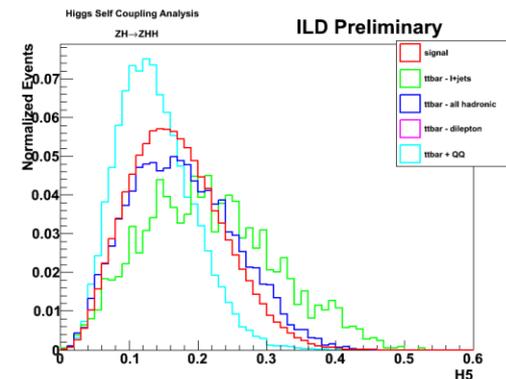
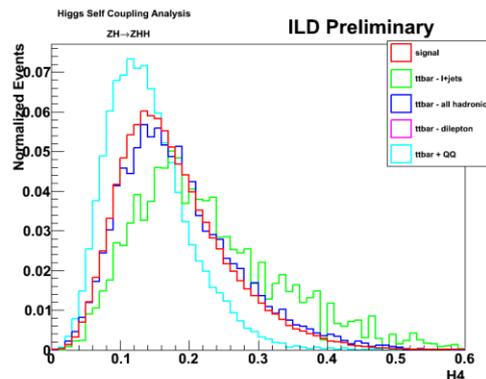
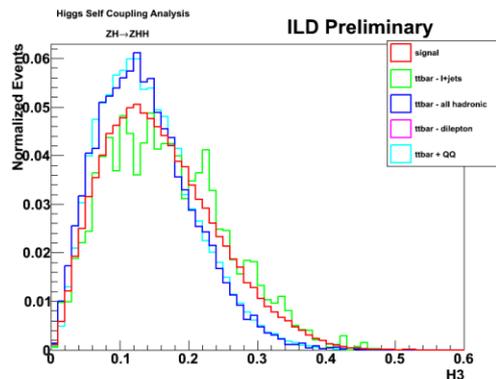
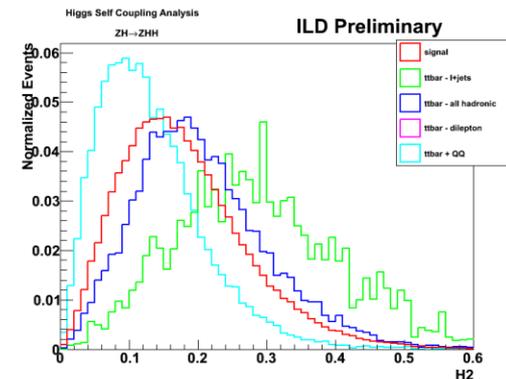
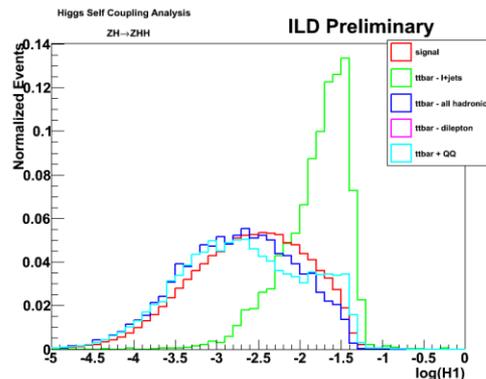
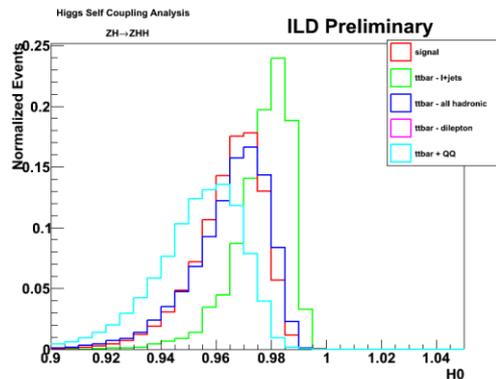


NON-SIMPLE VARIABLES USED FOR MVA

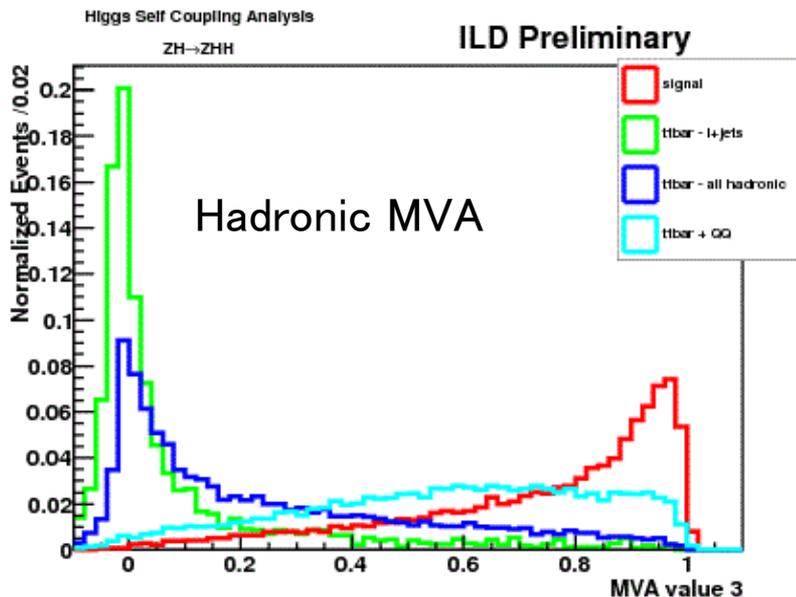
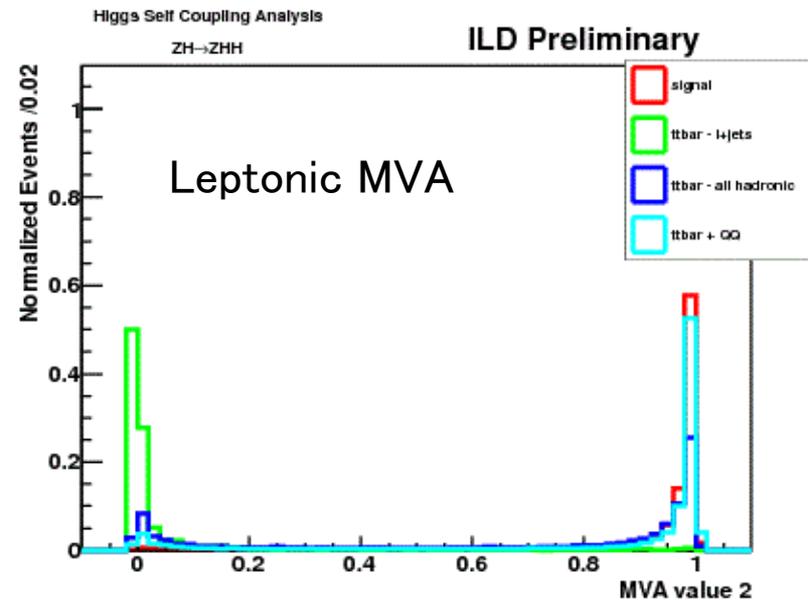
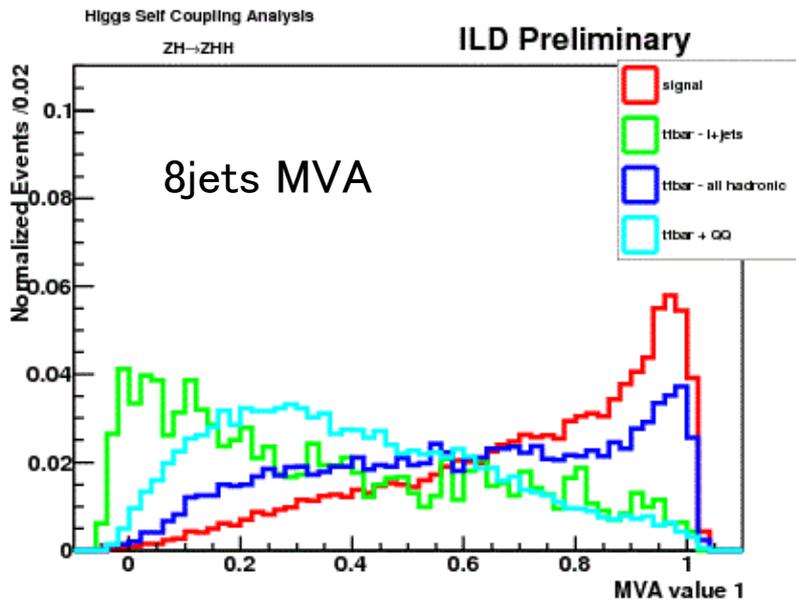
○ Fox-wolfram moments

$$H_l = \sum_{i,j} \frac{|\mathbf{p}_i| |\mathbf{p}_j|}{E_{\text{vis}}^2} P_l(\cos \theta_{ij}) ,$$

- P_l is Legendre polynomials
- Those moments characterize the structures of 2jets, 3jets, or isotropic events



MVA OUTPUTS EXAMPLES(ALLHADRONIC@500GeV)



cut of MVA:

$$\text{MVA}_{8\text{jets}} > 0.08$$

$$\text{MVA}_{\text{lep}} > 0.02$$

$$\text{MVA}_{\text{had}} > 0.74$$

SENSITIVITY@500GeV

○ $HH \rightarrow (bb)(WW)$

- As mentioned, categorized with decay types of Z and W boson
 - $Z \rightarrow bb, cc$ or ll
- b-tagging strategy – introduce looser b-tag category
 - 4-btag & 3-btag
- $E_{CM} = 500\text{GeV}$, $L = 2\text{ab}^{-1}$
- **Significance $\sim 1.91 \sigma$**

Modes	Z decay	b tag	Signal	Background	Significance
All hadronic	$Z \rightarrow bb$	4btag	15.20	87.52	1.50σ
		3btag	19.43	3099.49	0.35σ
	$Z \rightarrow cc$		11.29	366.13	0.58σ
Lepton + jets	$Z \rightarrow bb$		1.65	17.62	0.38σ
	$Z \rightarrow cc$		1.50	819.61	0.05σ
Dilepton	$Z \rightarrow ll$		2.24	8.44	0.69σ
Trilepton	$Z \rightarrow ll$		1.05	2.60	0.55σ
Combined					1.91σ

SENSITIVITY@1TeV

○ HH→(bb)(WW)

- As mentioned, categorized with decay types of Z and W boson
 - Z→bb and ll, VBF channel
- b-tagging strategy – fully used the b-tagging for each category
- $E_{CM}=1\text{TeV}$, $L=2\text{ab}^{-1}$
- **Significance $\sim 2.80\sigma$**

Modes	Z decay	Signal	Background	Significance
All hadronic	Z→bb	17.15	48.17	2.12 σ
Lepton + jets	Z→bb	1.16	9.24	0.36 σ
Dilepton	Z→ll	1.03	14.30	0.26 σ
6jets+ Missing	No Z, $\nu\nu$ HH	6.90	8.24	1.77 σ
Combined				2.80 σ

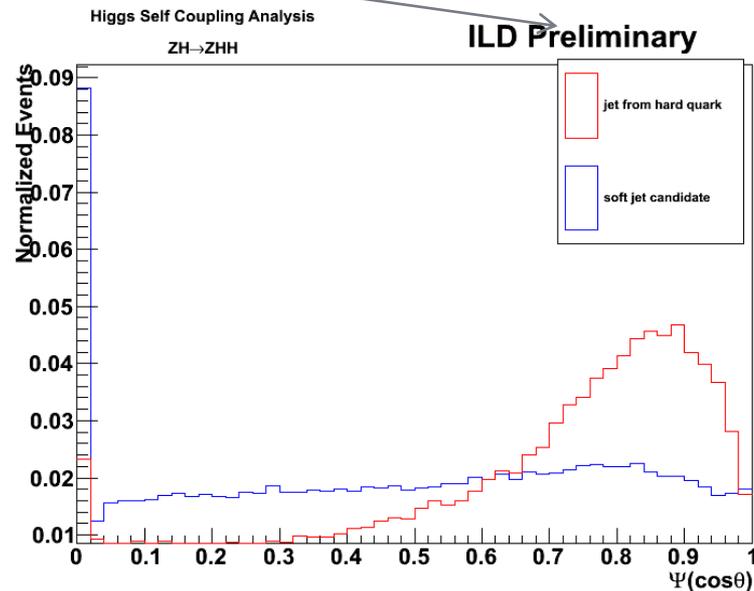
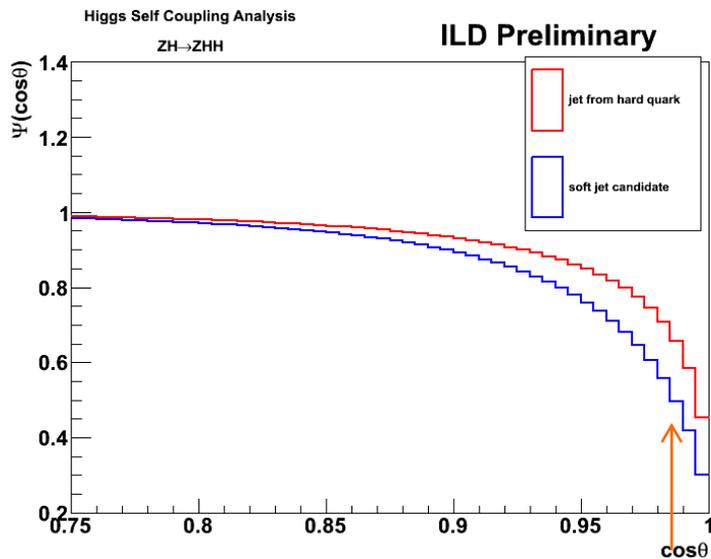
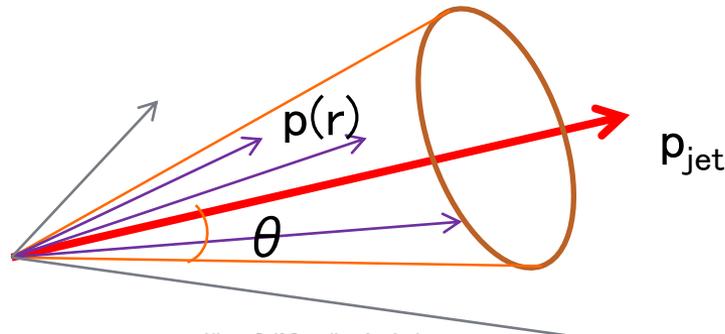
SUMMARY AND PLAN

- Higgs self coupling analysis using the events with $H \rightarrow WW^*$ is ongoing.
 - Multi variate analysis to reject the backgrounds
 - Total sensitivity @500GeV is $\sim 1.91 \sigma$
 - Total sensitivity @1TeV is $\sim 2.80 \sigma$
- **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

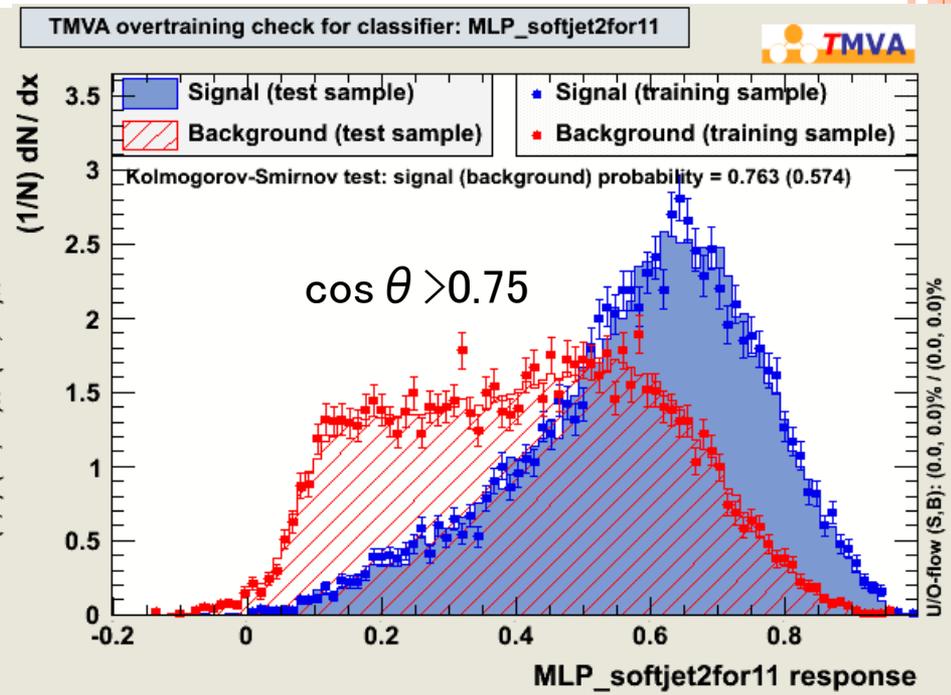
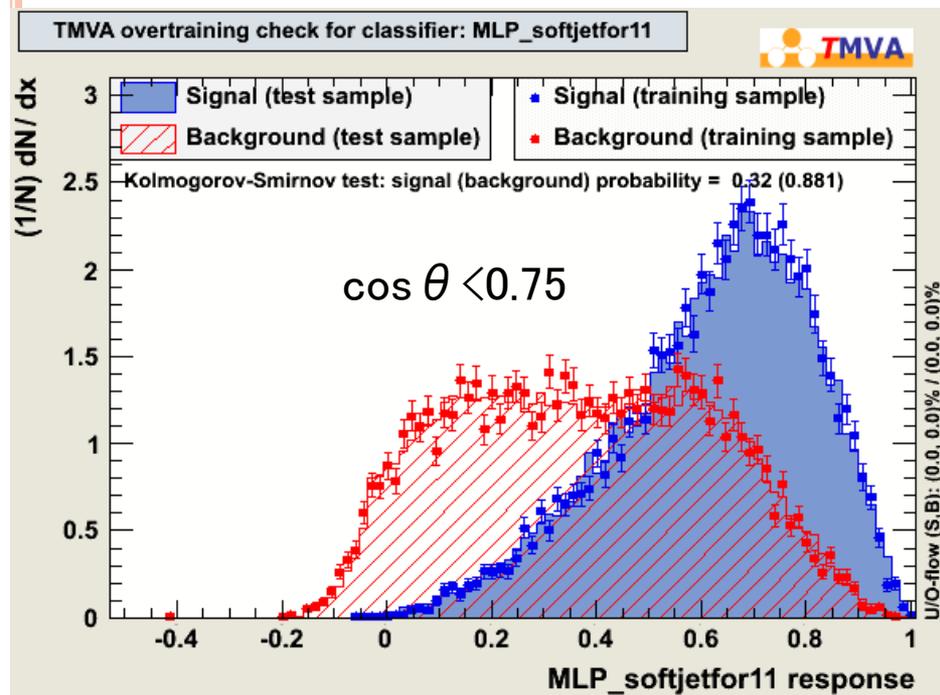
- Soft jet finding may be available for the events with extra jets not coming from hard process quarks
 - e.g. 8 jets requirement to $t\bar{t}$ hadronic events (6 jets from hard quarks)
- Traditional jet shape indicates the same tendency as hadron collider analysis

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



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: $\text{btag}(3) > 0.92$ && $\text{btag}(4) > 0.44$
- $\text{HH} \rightarrow \text{bbbb}$ 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
χ^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