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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

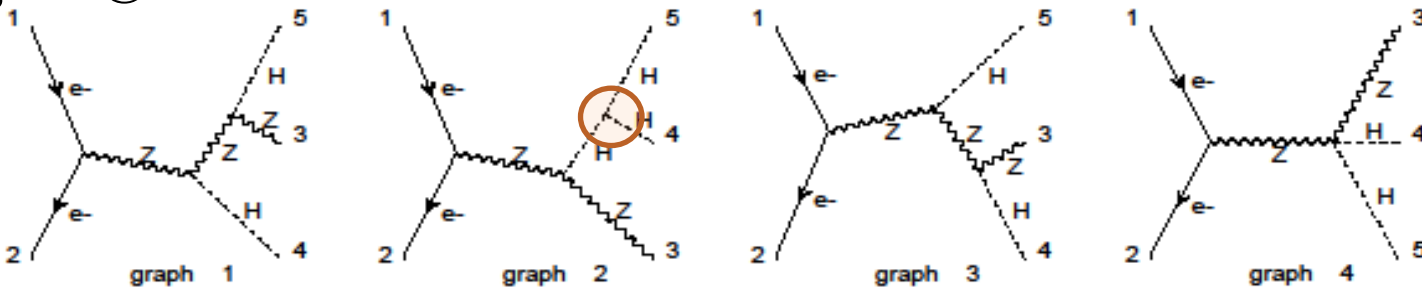
→ difficult to measure

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

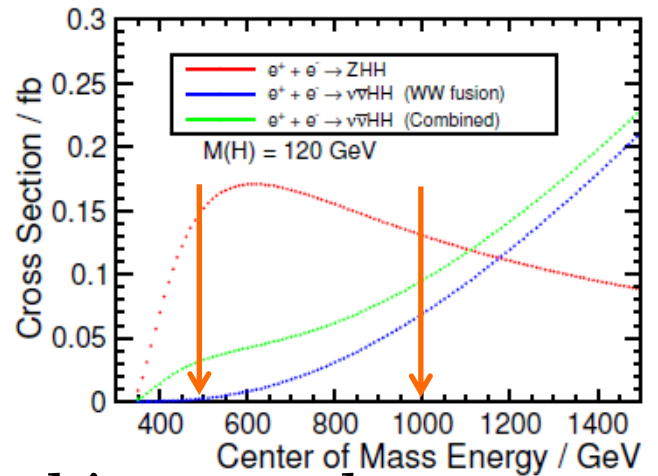
- Observing two Higgs bosons in the event is the only way to measure the self coupling
- Accurate test of the coupling may lead to the extended nature of Higgs sector → may go to new physics
- Our goal is to observe and measure the Higgs self coupling first

SIGNAL EVENTS

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

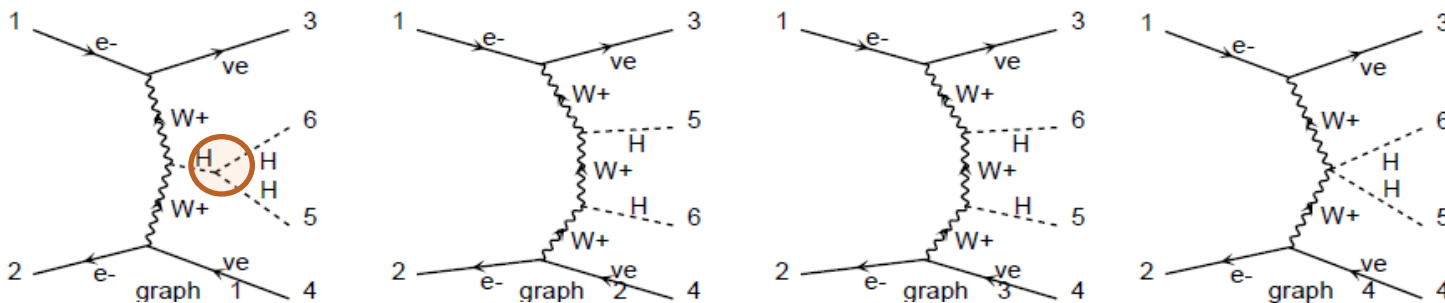


Signal: 2 Irreducible B.G.: 1, 3, 4



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

STATUS OF THIS ANALYSIS

Golden channel: $Z(bb)(bb)$

- b-tagging can suppress the backgrounds

Requirement of $H \rightarrow WW^*$ decay

- Same cross section as golden channel
- Contribution of the total sensitivity
- Need to reduce the backgrounds using kinematics of the events

	H1		
H2	Br	bb	WW
	bb	WW	WW

But...

Disadvantage of the analysis

- Num. of b-tagging available is fewer than the golden channel
- @1TeV, the number of b-tagging available is 2 in VBF process
→ very similar to lepton+jets with lepton missing events
- Background cross section is increased at higher energy
 - $t\bar{t} + X$, which is difficult to reject from Higgs Strahlung process

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

○ Simulation

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

process	$\sigma(\text{fb})$	$\sigma(\text{fb})$
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
ZZ + H	0.77	0.54
ZZZ	1.83	1.62

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

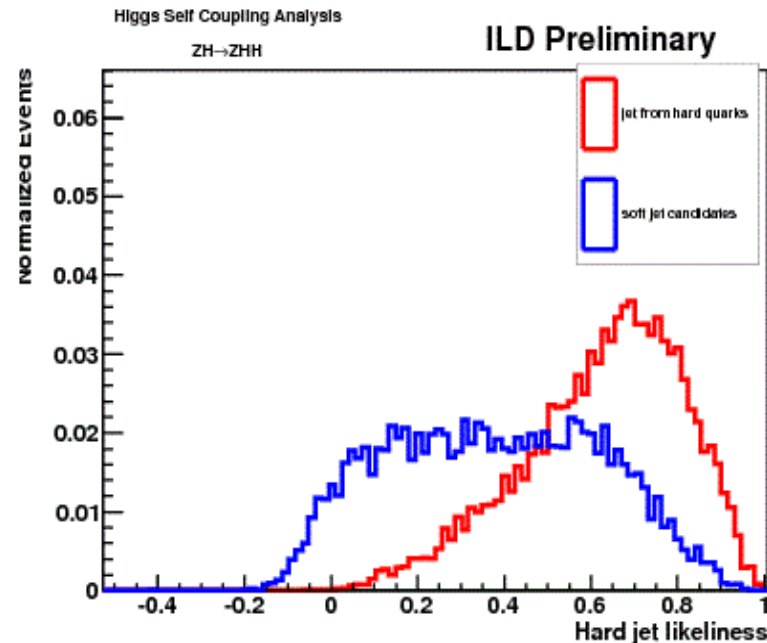
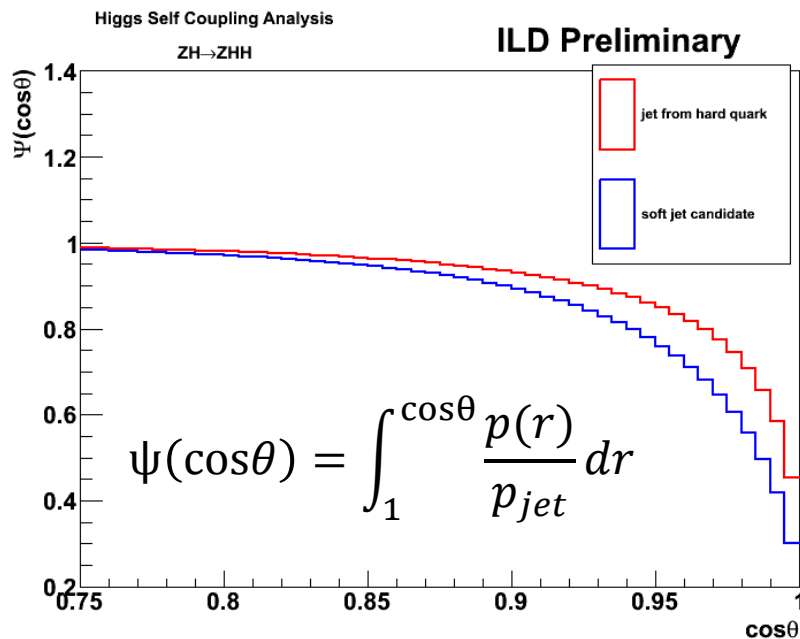
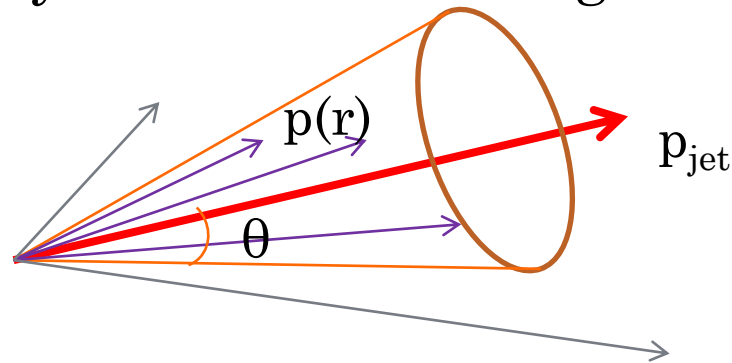
- Classify the events with Z and W decays:

@500GeV	$WW \rightarrow (qq)(qq)$	$WW \rightarrow (qq)(lv)$	@1TeV	$WW \rightarrow (qq)(qq)$	$WW \rightarrow (qq)(lv)$
$Z \rightarrow bb$	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

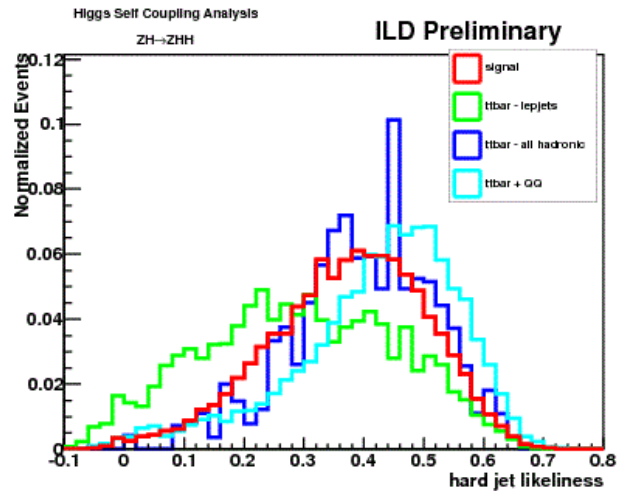
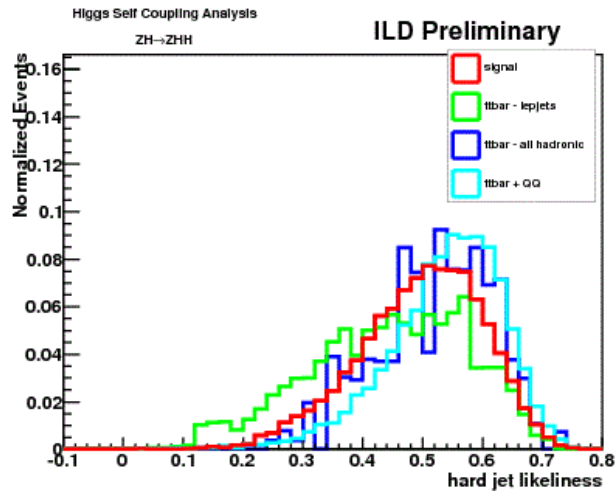
SOFT JET FINDING

- 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

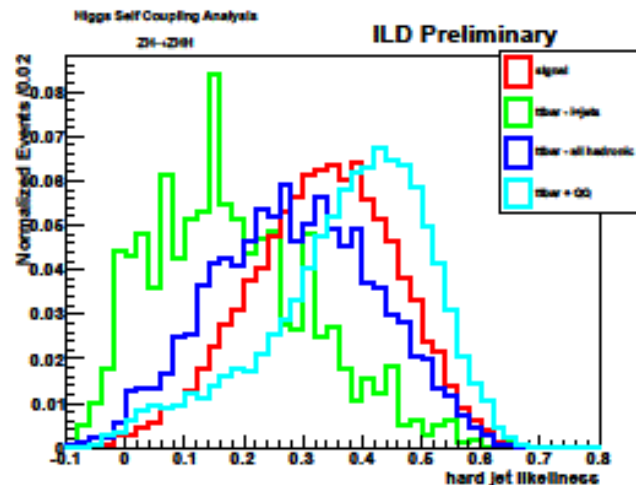
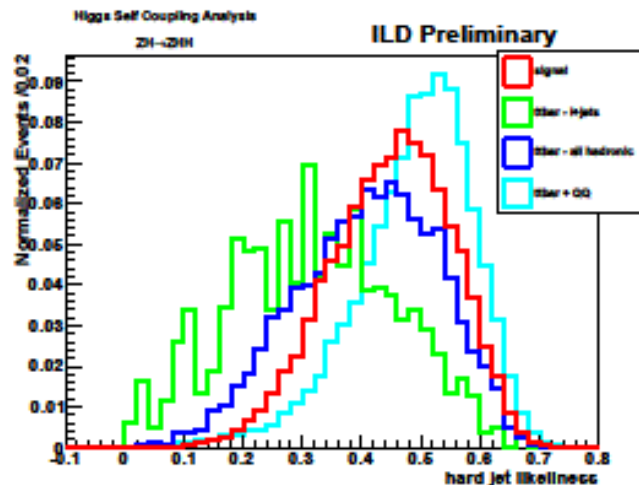


CHECK THE PERFORMANCE

- Check the jets with small hard jet likelihood – signal vs. $t\bar{t}$
- For 6jets



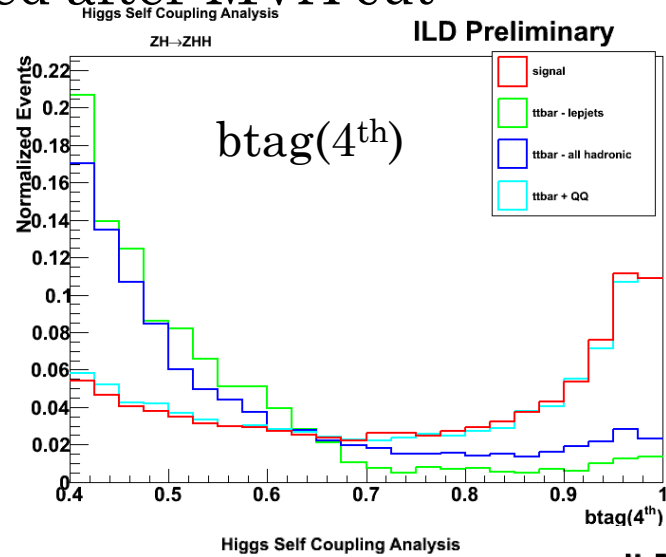
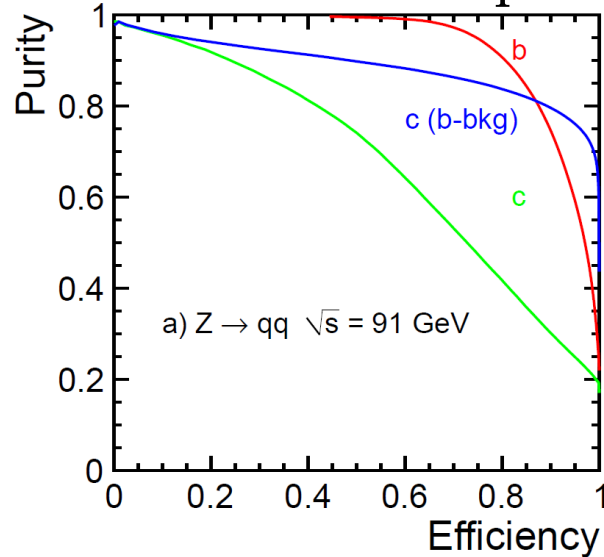
- For 8jets



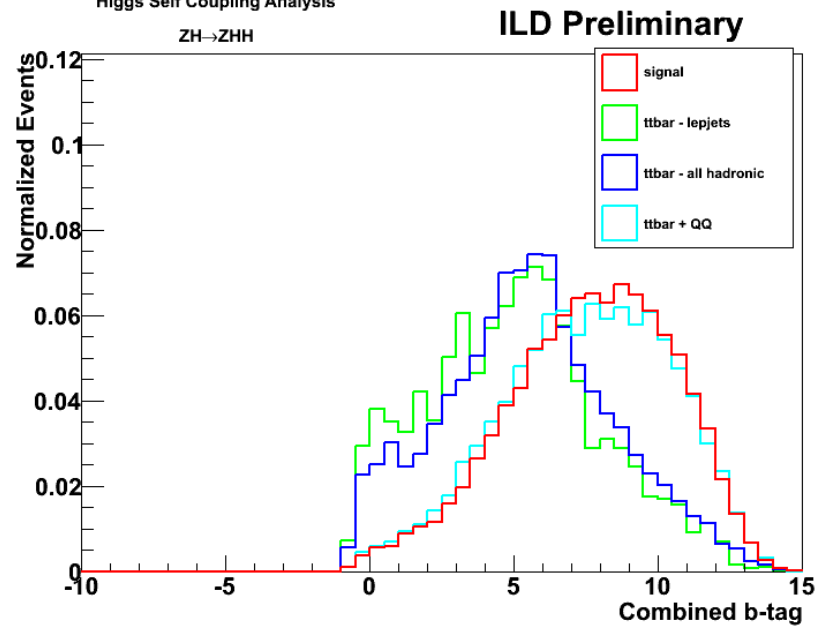
FLAVOR TAGGING

Using LCFIPlus

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



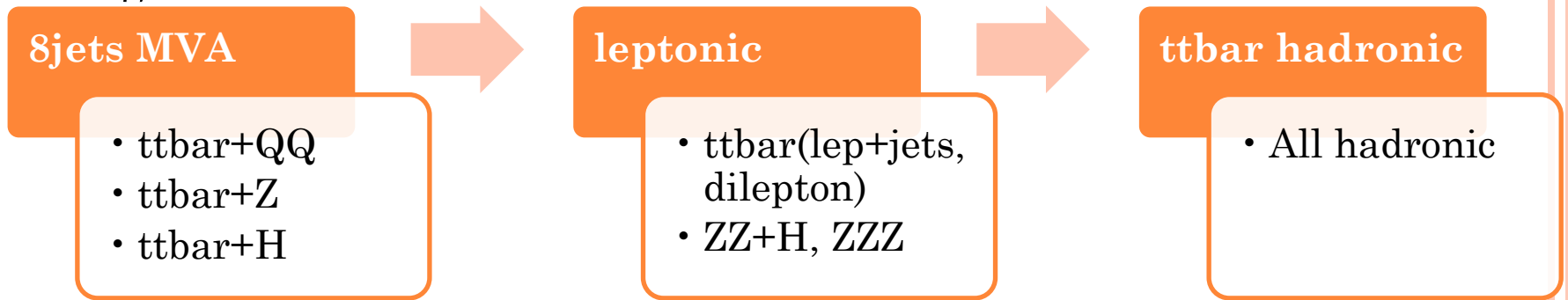
- Introduce combined b-tagging
 - After solving the jet pairing
 - $b(\text{Combined}) = \log\left(\frac{b_1 b_2}{(1-b_1)(1-b_2)}\right)$
 - Use as an input variable for MVA



BACKGROUND REJECTION

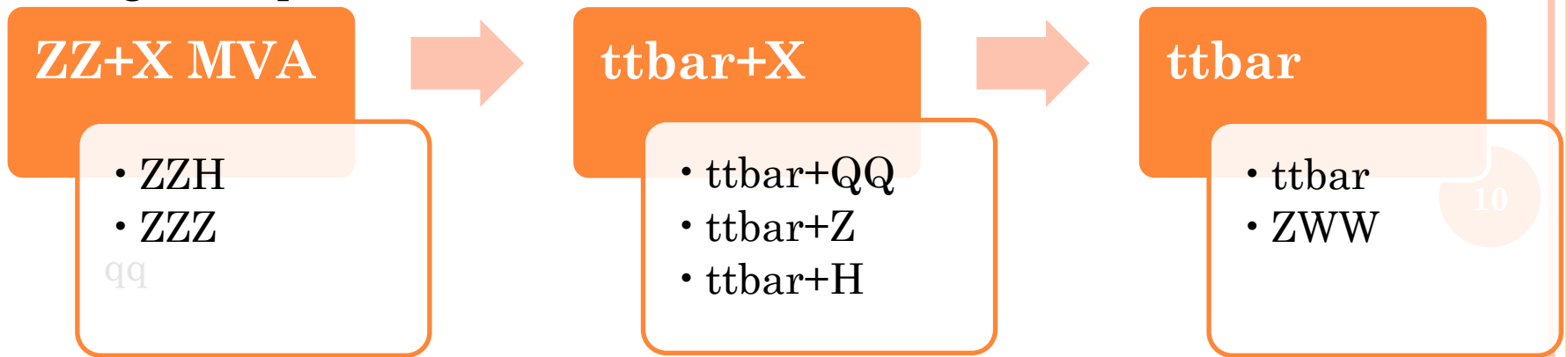
Multi Variate Analysis @500GeV

- 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:



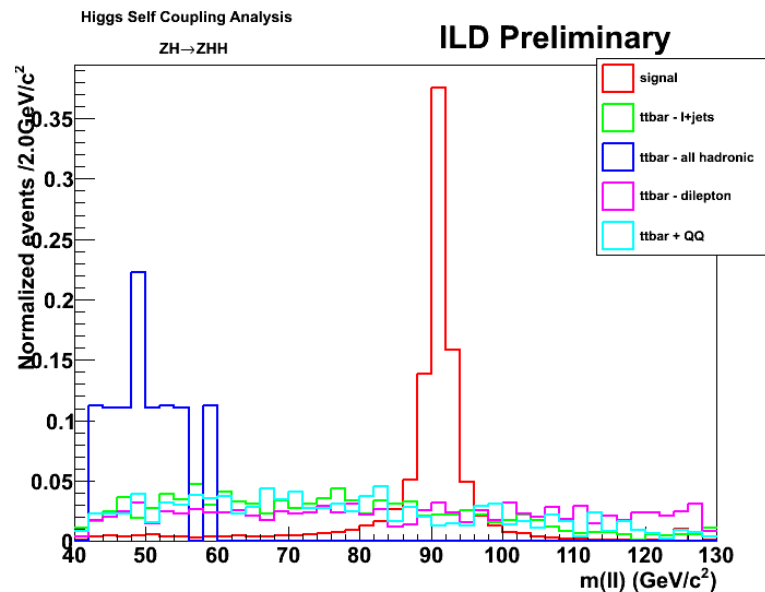
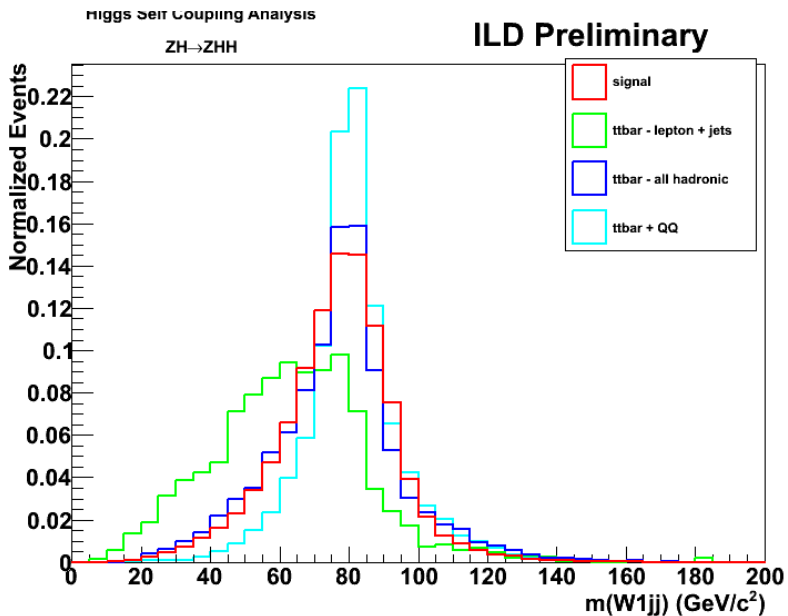
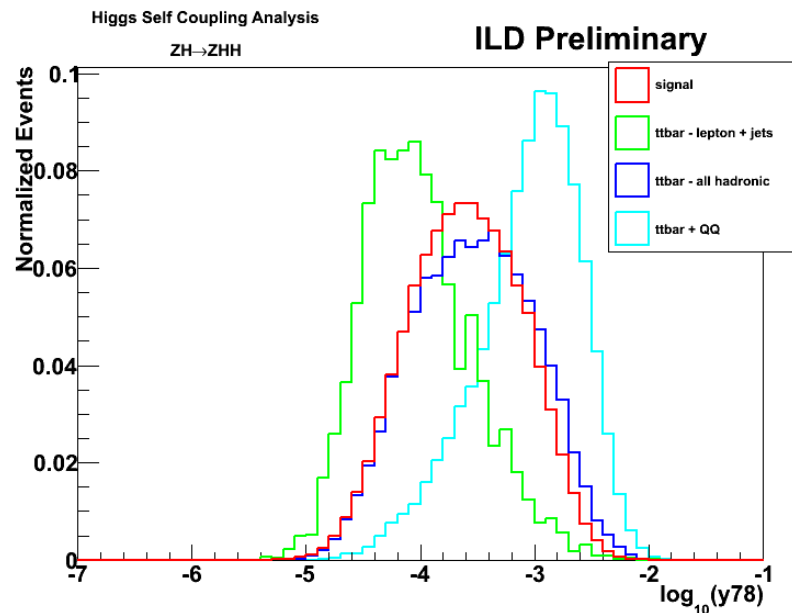
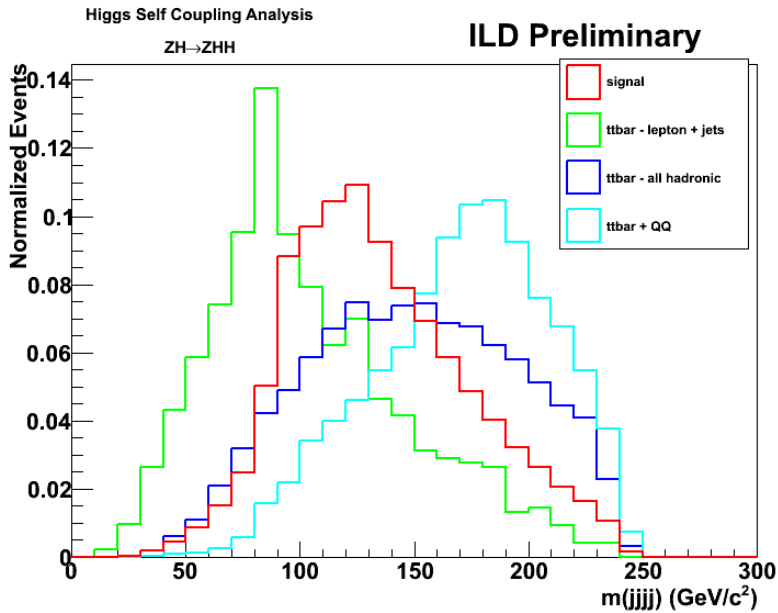
Multi Variate Analysis @1TeV

- Same strategy as the case of 500GeV
- e.g. VBF process



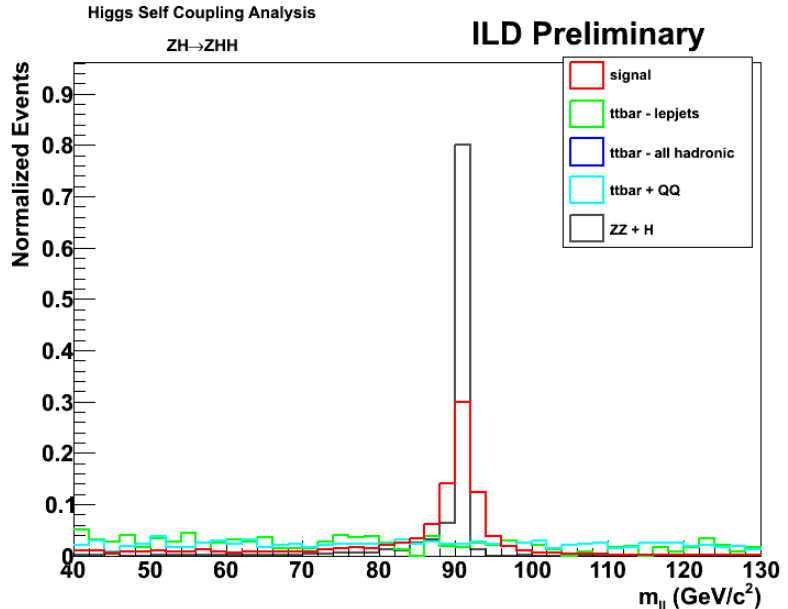
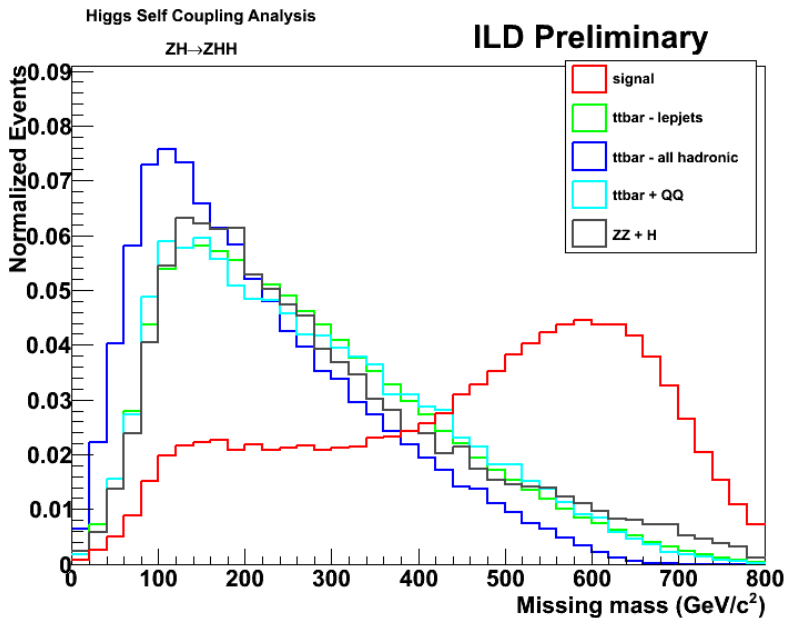
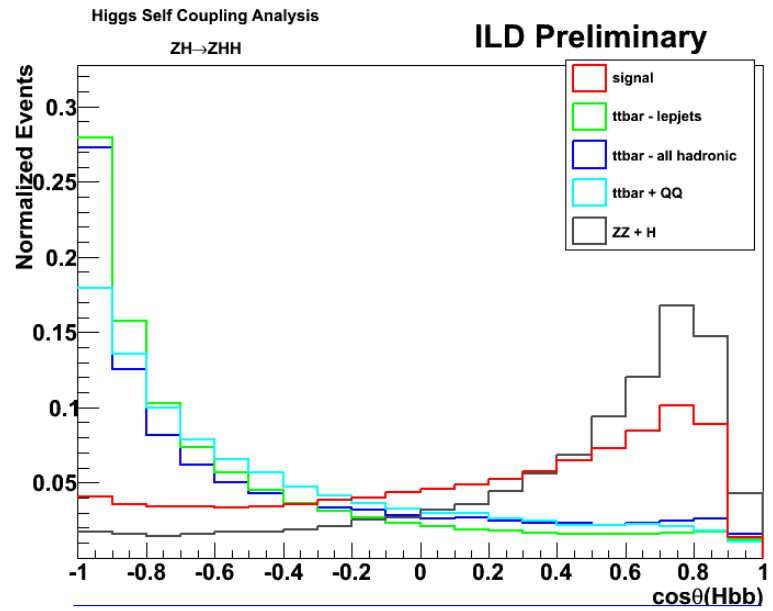
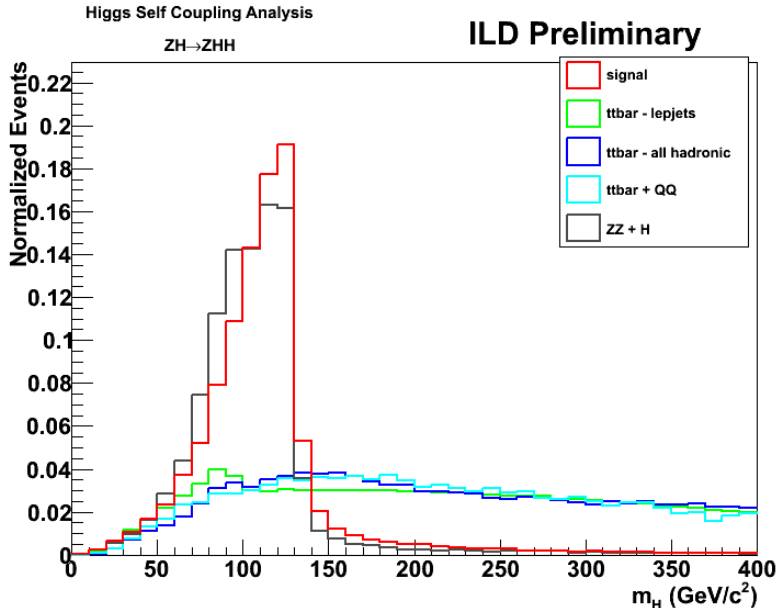
SOME KINEMATIC VARIABLES USED FOR MVA

Very powerful variable @500GeV: $m(jjjj)$, $m(lvjj)$



SOME KINEMATIC VARIABLES USED FOR MVA

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



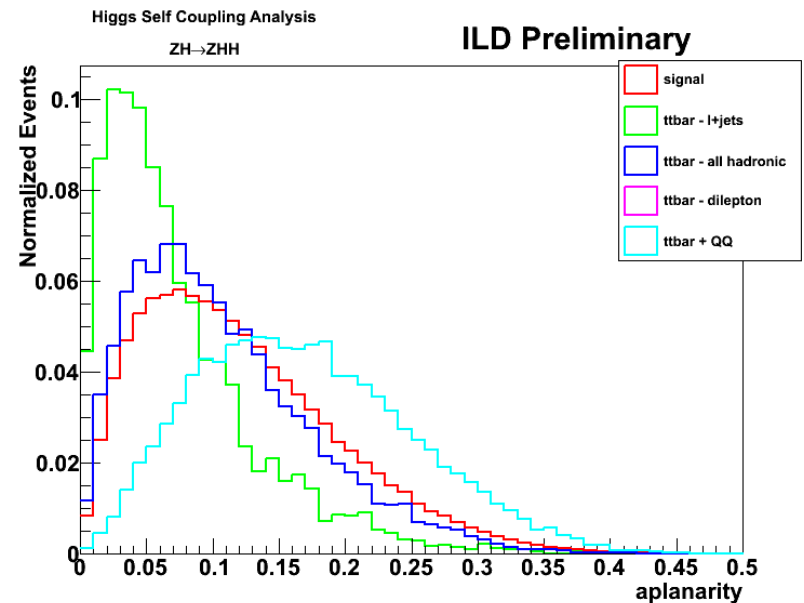
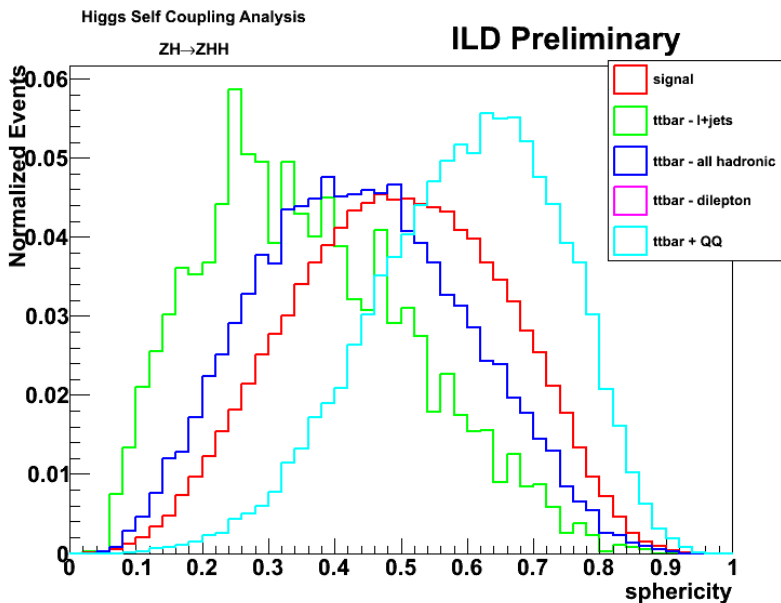
NON-SIMPLE VARIABLES USED FOR MVA

○ 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

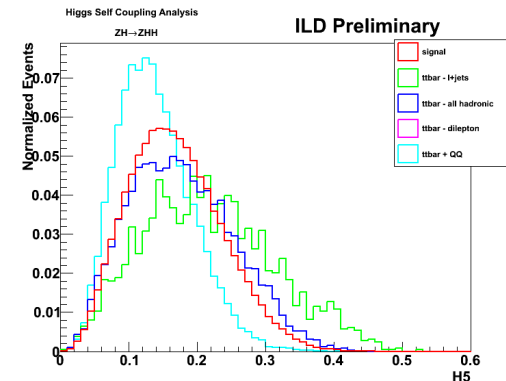
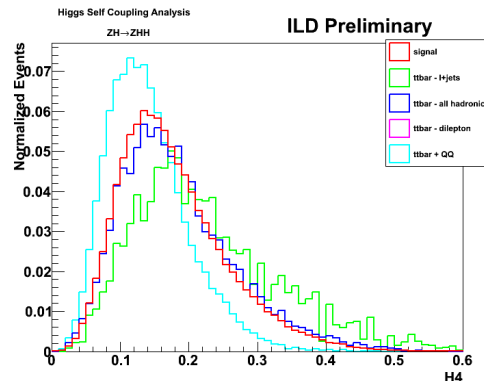
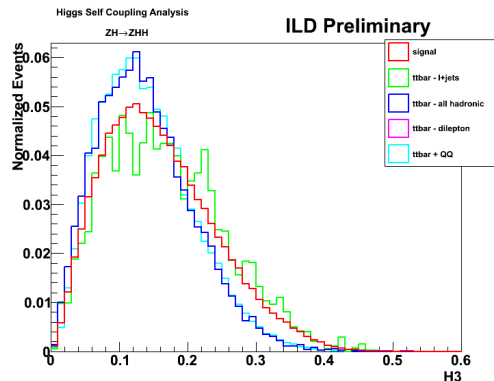
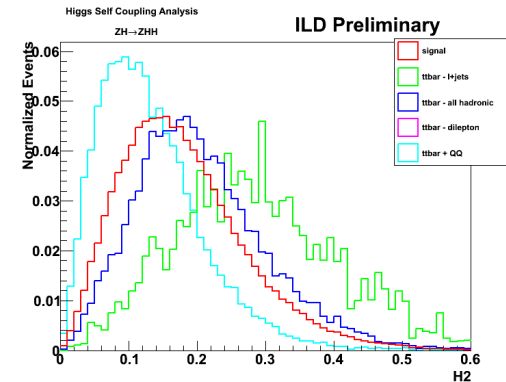
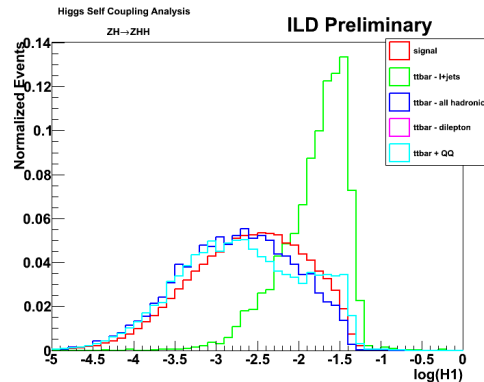
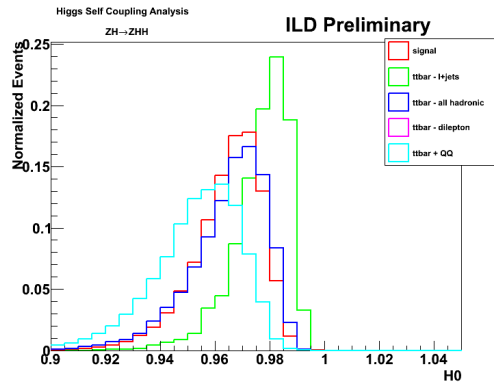


NON-SIMPLE VARIABLES USED FOR MVA

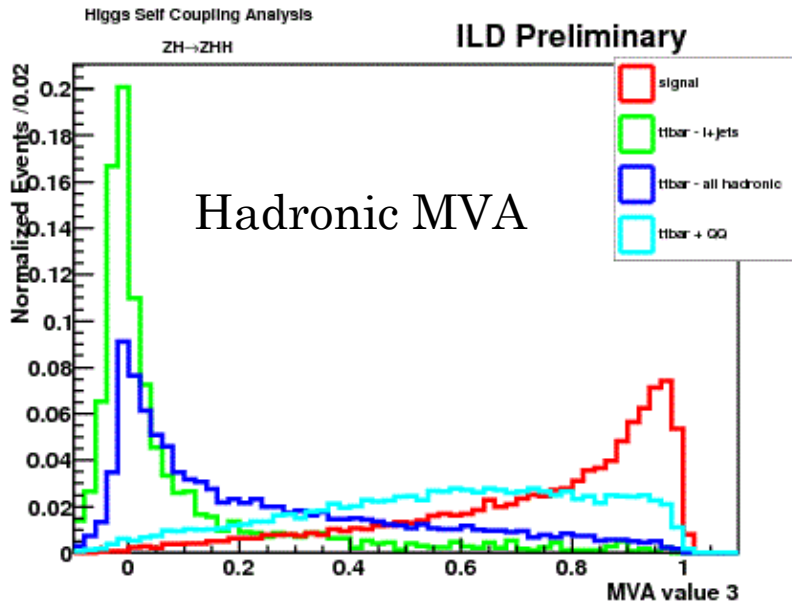
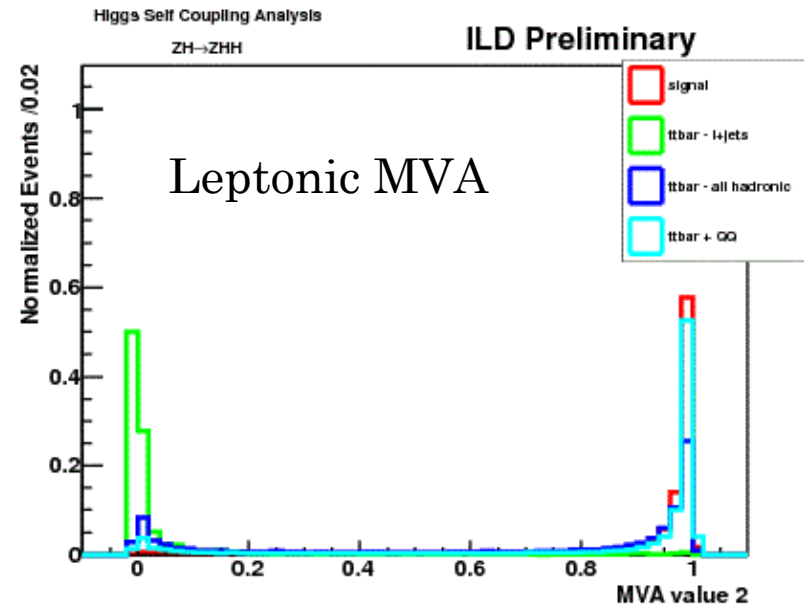
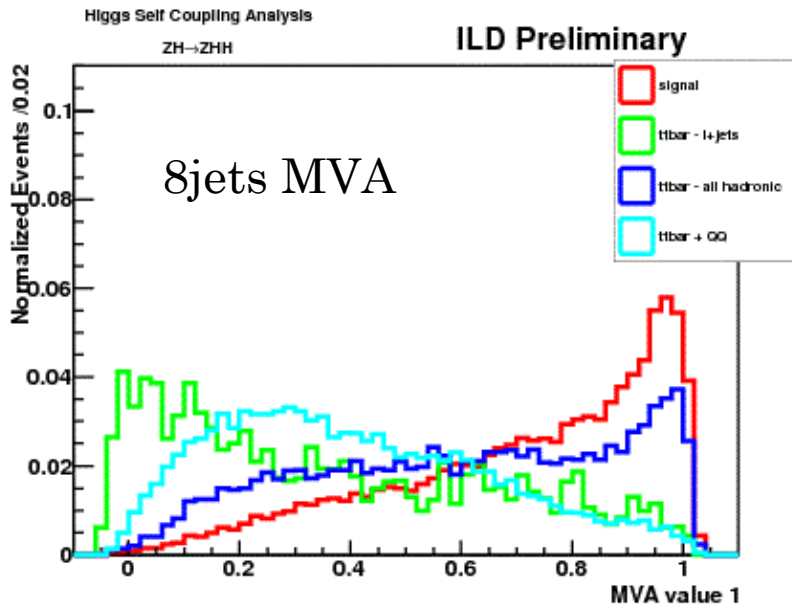
○ Fox-wolfram moments

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

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

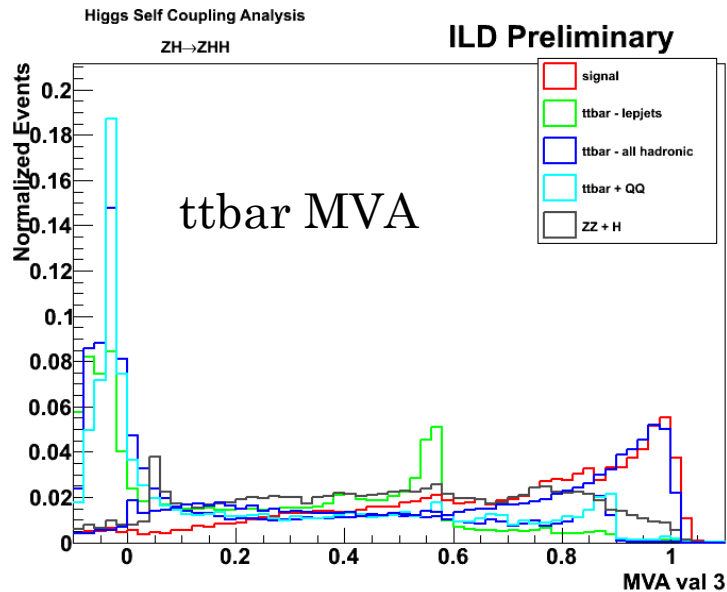
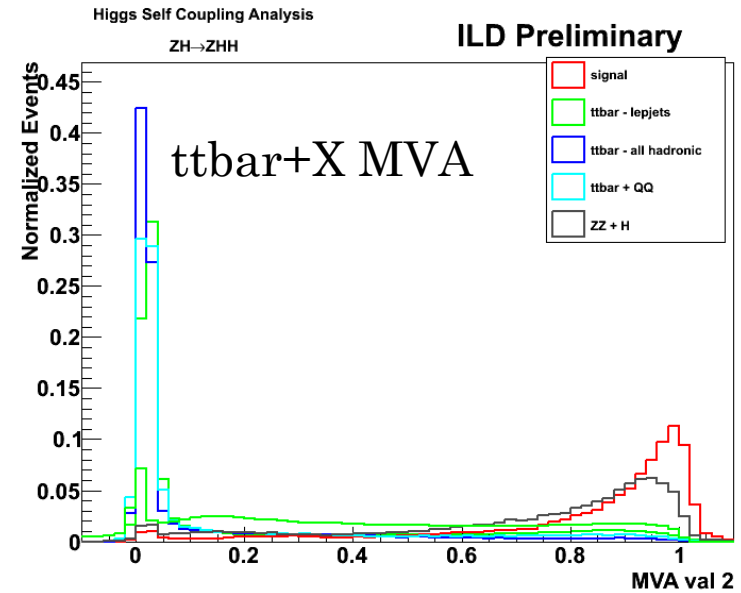
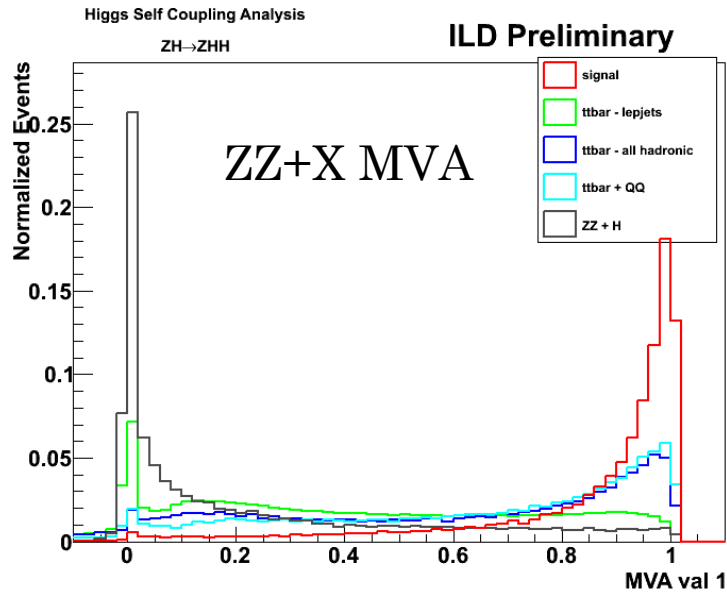


MVA OUTPUTS EXAMPLES(ALLHADRONIC@500GEV)



cut of MVA:
 $MVA_{8jets} > 0.08$
 $MVA_{lep} > 0.02$
 $MVA_{had} > 0.74$

MVA OUTPUTS EXAMPLES(NNHH@1TeV)



cut of MVA:

- $MVA_{ZZX} > 0.34$
- $MVA_{ttbarX} > 0.86$
- $MVA_{ttbar} > 0.91$

SENSITIVITY@500GeV

○ HH→(bb)(WW)

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

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

SENSITIVITY@1TeV

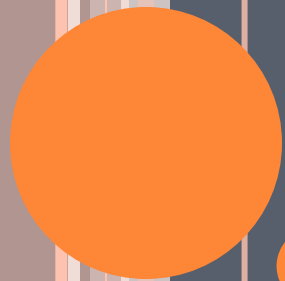
○ HH→(bb)(WW)

- 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
- $E_{\text{CM}}=1\text{TeV}$, $L=2\text{ab}^{-1}$
- **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, vvHH	6.90	8.24	1.77 σ
Combined				2.80σ

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



BACKUPS

EVENT SELECTION

○ Lepton selection

- Lepton ID: The isolated lepton coming from the primary vertex

lepton	electron	muon
cut	$0.65 < E/p < 1.25$ $E(\text{EM}) / (E(\text{EM}) + E(\text{HAD})) > 0.90$ $ d_0 < 0.02$ $ z_0 < 0.02$ Cone Energy $< 61.10 - 0.28P$	$E/p < \min(0.5, 10.0/E)$ $E(\text{EM}) / (E(\text{EM}) + E(\text{HAD})) < 0.45$ $ d_0 < 0.02$ $ z_0 < 0.02$ Cone Energy $< 52.45 - 0.28P$

- Detection efficiency of Lepton ID $\sim 98.4\%$ for lep+jets signal events

	Signal	ttbar – lep+jets	ttbar - allhad
Efficiency(%)	98.4	71.4	7.9

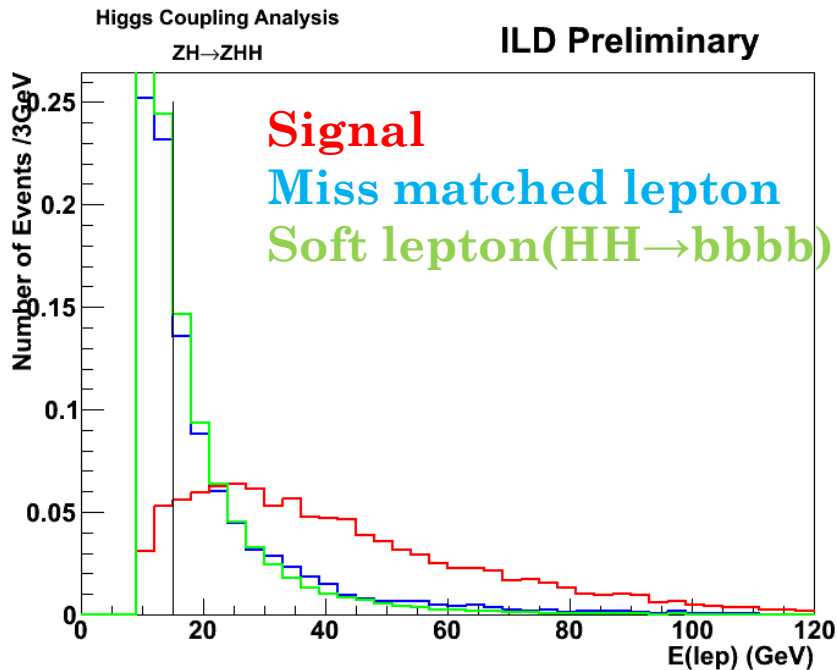
- For dilepton events $\sim 83.8\%$ of signal events

	Signal	ttbar – dilepton
Efficiency(%)	83.8	84.5

EVENT SELECTION

○ Lepton selection

- $E(\text{lep}) > 15\text{GeV}$ is required to suppress soft leptons
- Dividing into 3 samples:
 - one lepton for **lepton + jets**
 - two leptons for **dilepton** → opposite charge & same flavor
 - three leptons for **trilepton** → looking for the lepton pair from Z
 - tight lepton veto for **all hadronic**

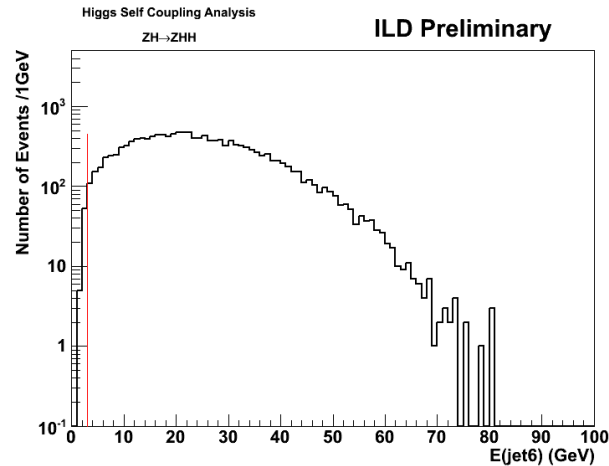
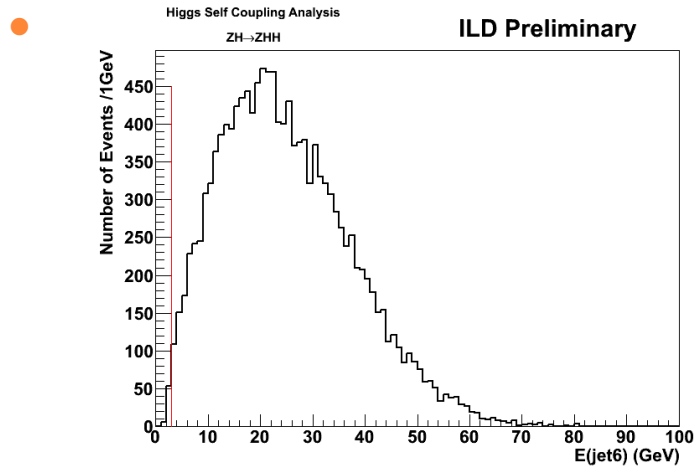


Lepton matching is required:
 $\cos\theta > 0.9$

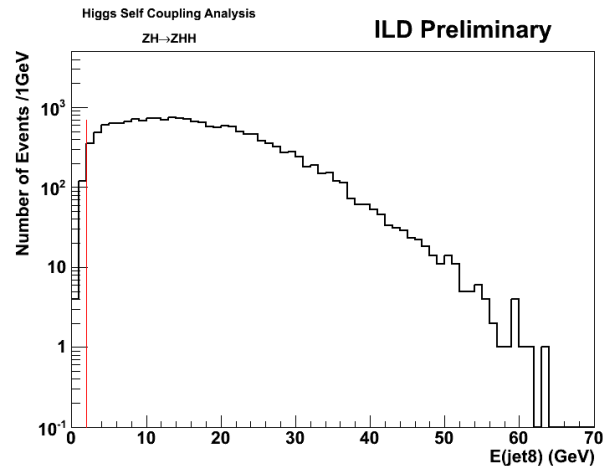
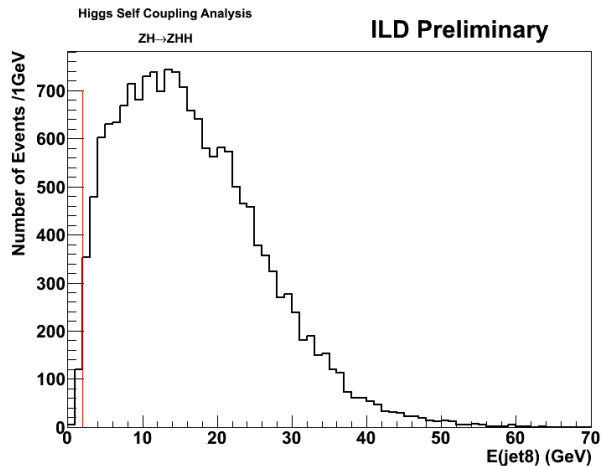
EVENT SELECTION

○ jet selection

- requiring 4jets, 6 jets or 8 jets using LCFIPlus & Durham
- $E(\text{jet}) > 3\text{GeV}$ is required to care the lowest energy jet for **6 jets** case



- $E(\text{jet}) > 2\text{GeV}$ is required to care the lowest energy jet for **8 jets** case



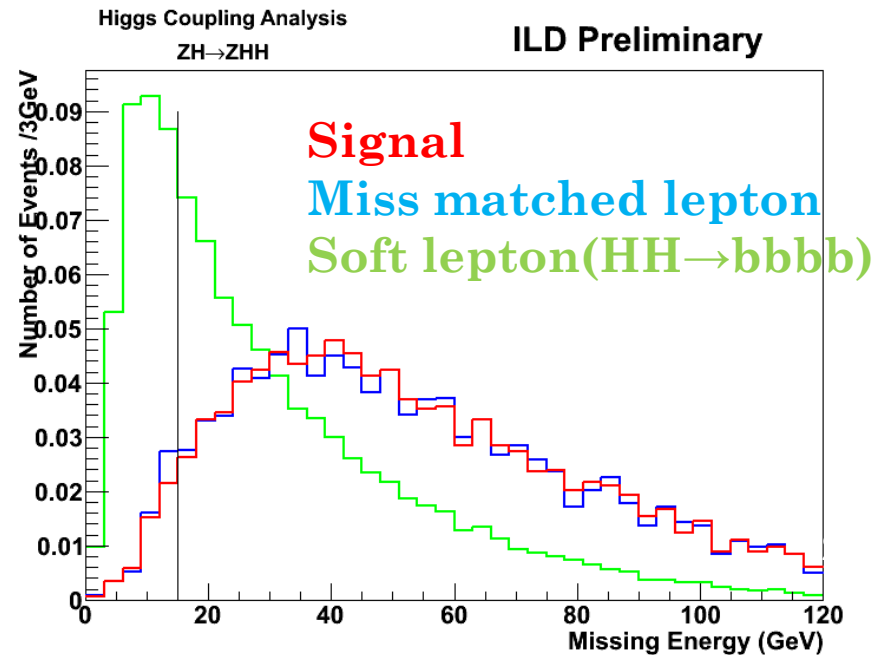
EVENT SELECTION

- Detection efficiency after the jet energy cut:

signal	4jets requirement	6jets requirement	8jets requirement
Efficiency(%)	99.0	99.4	99.6

- Missing momentum

- **lepton + jets**: $P(\text{Miss}) > 15 \text{ GeV}/c$ to suppress $\text{HH} \rightarrow \text{bbbb}$ events
- **All hadronic & dilepton**: $P(\text{Miss}) < 80 \text{ GeV}/c$ required
- **Trilepton**: $P(\text{Miss}) < 150 \text{ GeV}/c$ to gain the acceptance



EVENT SELECTION & MAKING SAMPLES

○ preselection

- lepton selection – looking for isolated leptons
 - Electron and muon from primary vertex
 - Lepton energy cut – $E > 15 \text{ GeV}$ to reject soft leptons
 - **Divide into orthogonal samples based on the lepton number in the events**
 - From 0 to 3
 - For 2 and 3 lepton samples, looking for a lepton pair from Z boson
- Jet selection – jet clustering
 - Require proper number of jets for each sample – 4, 6, or 8 jets
 - Minimum jet energy cut is required to reject trivial backgrounds

	4jets	6jets	8jets
Min. Energy(GeV)	1.0	3.0	2.0

- b likeliness > 0.4 is required for b jet candidates
- Missing momentum

Category(Lep. Num.)	0	1	2	3
P(Miss) (GeV/c)	$P < 80$	$P > 15$	$P < 80$	$P < 150$

SOLVING THE COMBINATION OF JETS

- Jets should be assigned to their parent particles correctly to obtain good kinematic variables

- **Jet pairing is based on the χ^2 technique**

- b jet assignment to Higgs and Z boson:

$$\chi^2 = \frac{(m_1 - m_Z)^2}{\sigma_Z^2} + \frac{(m_2 - m_H)^2}{\sigma_H^2}$$

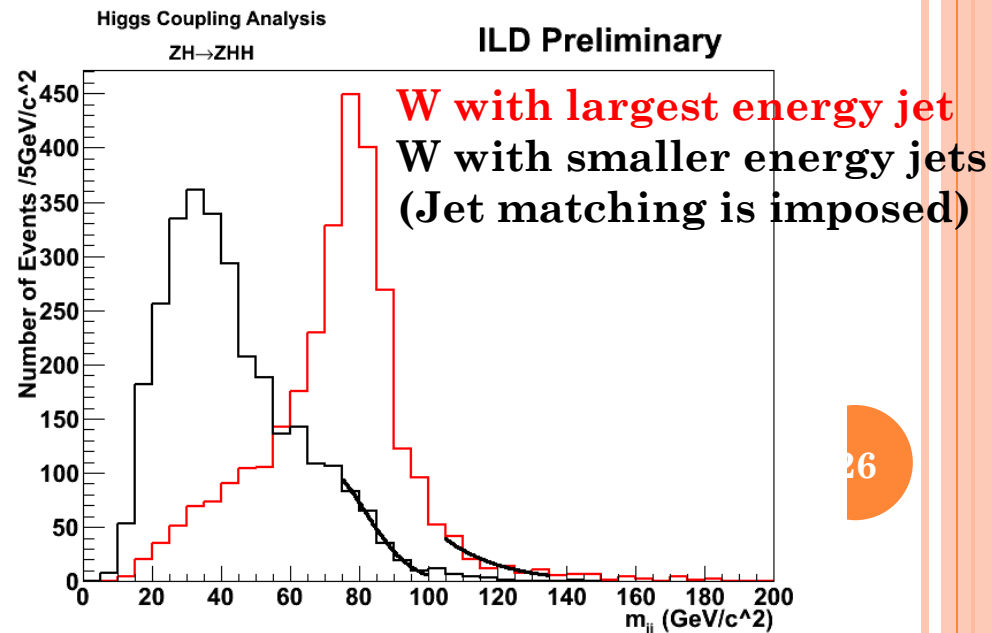
- Light flavor jet assignment to 2 W bosons:

- Mass constraint is imposed only to the W boson with largest energy jets

- Breit-Wigner is assumed

for W mass shape

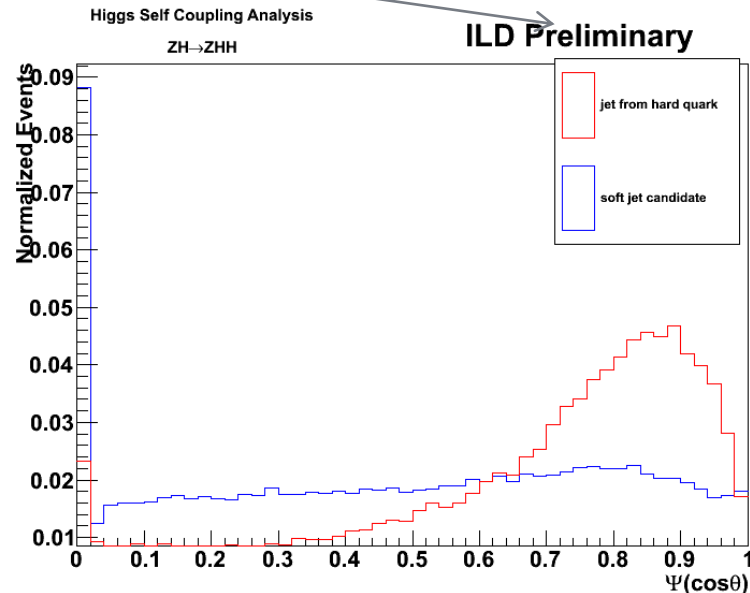
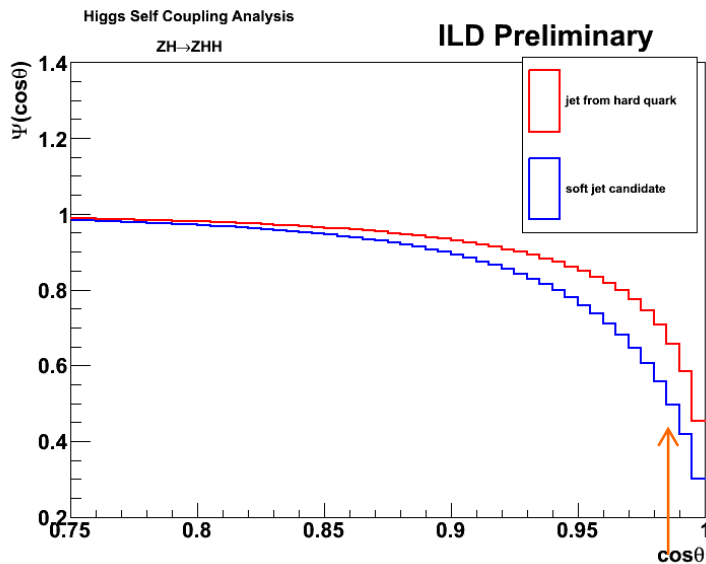
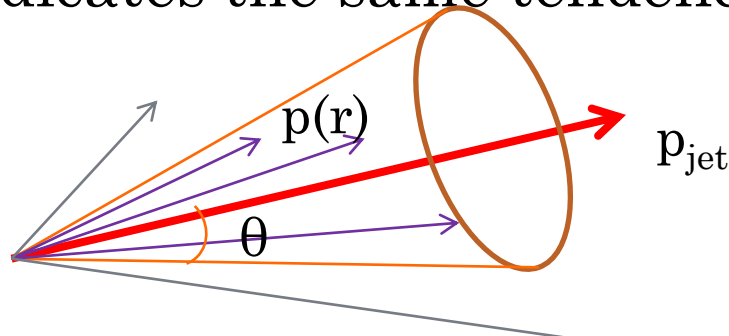
- $\chi^2 = -2\text{Log}(\text{BW}(m_{W1}|m_W, \Gamma_W))$



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

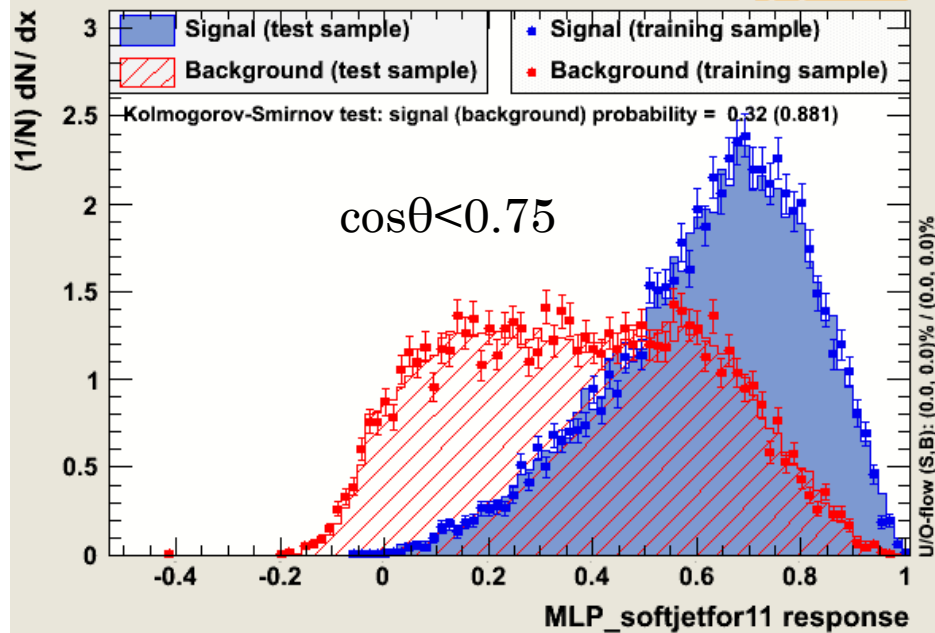
$$\psi(\cos\theta) = \int_1^{\cos\theta} \frac{p(r)}{p_{jet}} dr$$



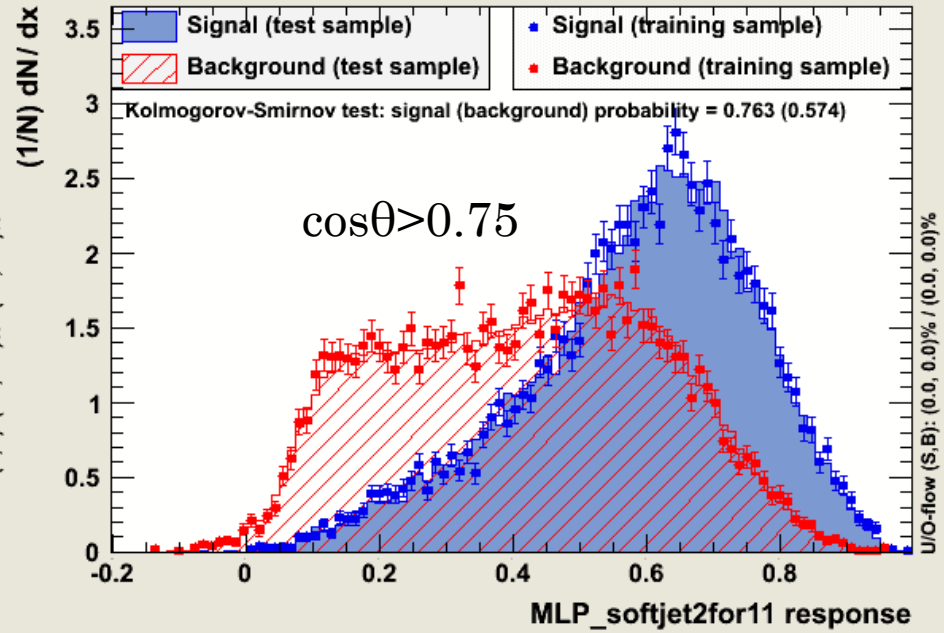
SOFT JET FINDING

- 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

TMVA overtraining check for classifier: MLP_softjetfor11



TMVA overtraining check for classifier: MLP_softjet2for11



REDUCTION TABLE

All hadronic

- Final b-tagging: $b_{\text{tag}}(3) > 0.92$ && $b_{\text{tag}}(4) > 0.44$
- $HH \rightarrow bbbb$ 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