HIGGS SELF COUPLING ANALYSIS USING THE EVENTS CONTAINING H→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

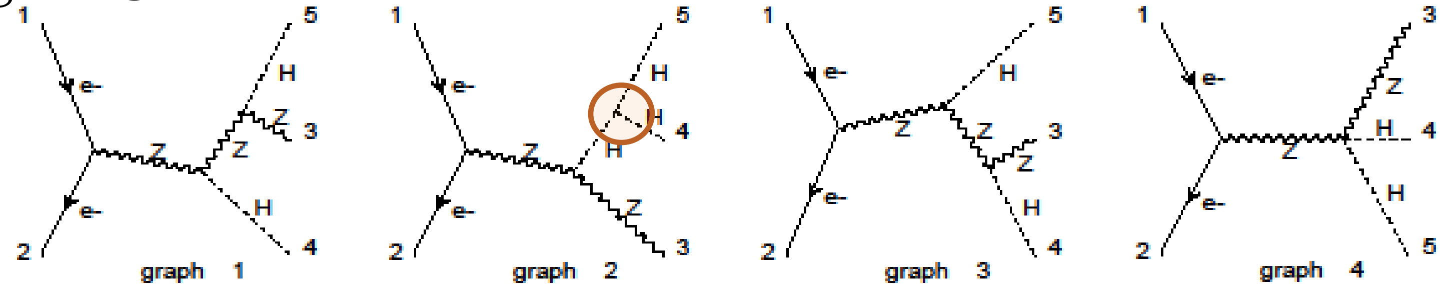
$SM: \quad \lambda = \frac{m_H^2}{2v^2} \quad v \sim 246 GeV$

Quartic coupling
→difficult to measure

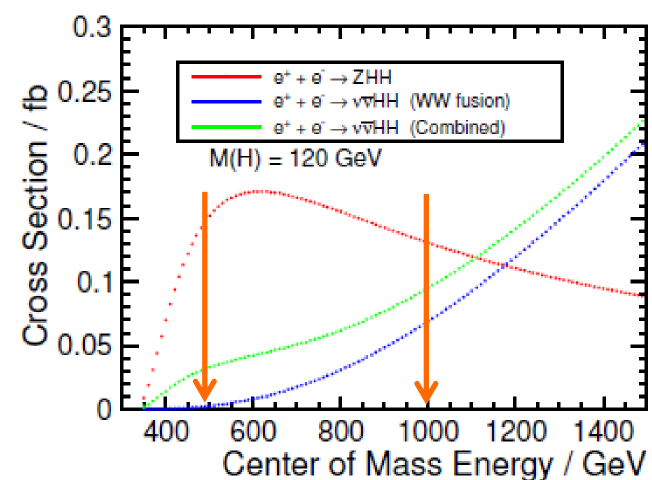
- Observing two Higgs bosons in the event is the only way to measure the self coupling
- Accurate test of the coupling may lead to the extended nature of Higgs sector → may go to new physics
- Our goal is to observe and measure the Higgs self coupling first

Signal Events

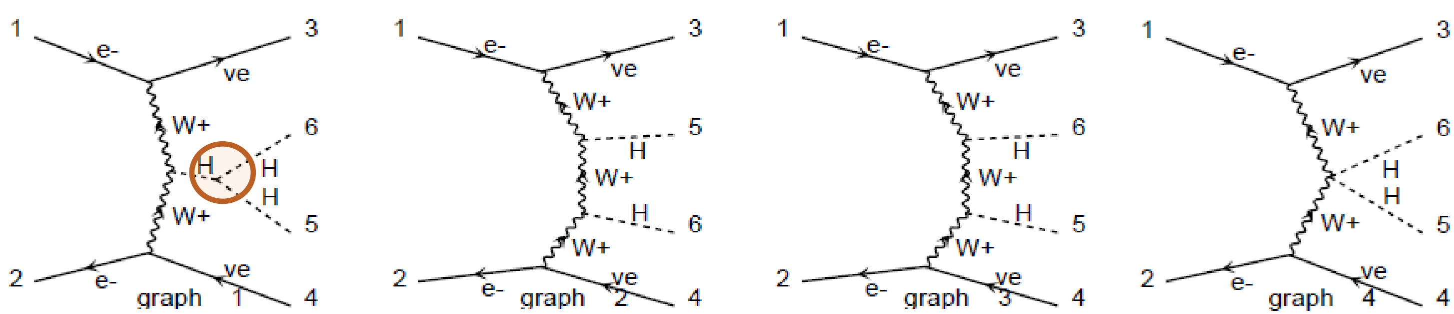
- Signal@500GeV - $e^+e^- \to Z^* \to ZH \to ZHH$ can be used



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



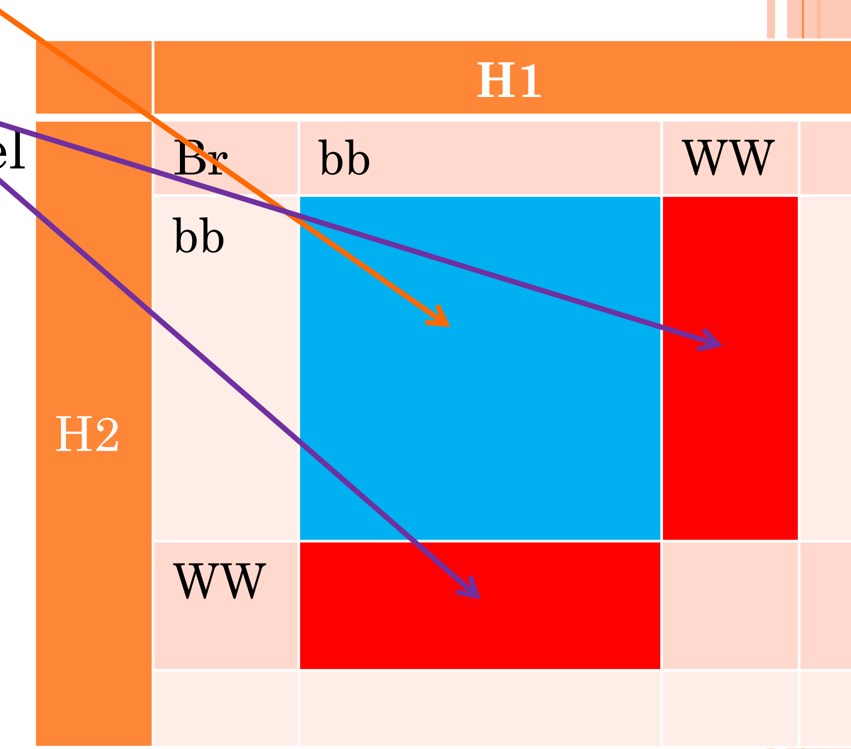
- Signal@1TeV – VBF $e^+e^- \to \nu\nu HH$ channel is opened
  - Increase the cross section of VBF



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

Status of this analysis

- Golden channel: Z(bb)(bb)
  - b-tagging can suppress the backgrounds
- Requirement of **H→WW*** decay
  - Same cross section as golden channel
  - Contribution of the total sensitivity
  - Need to reduce the backgrounds using kinematics of the events



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
    - ttbar+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(GeV/c^2)	125	125
simulator	Full with DBD	Fast

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
ZZ + H	0.77	0.54
ZZZ	1.83	1.62

Analysis strategy for HH→(bb)(WW)

- Classify the events with Z and W decays:

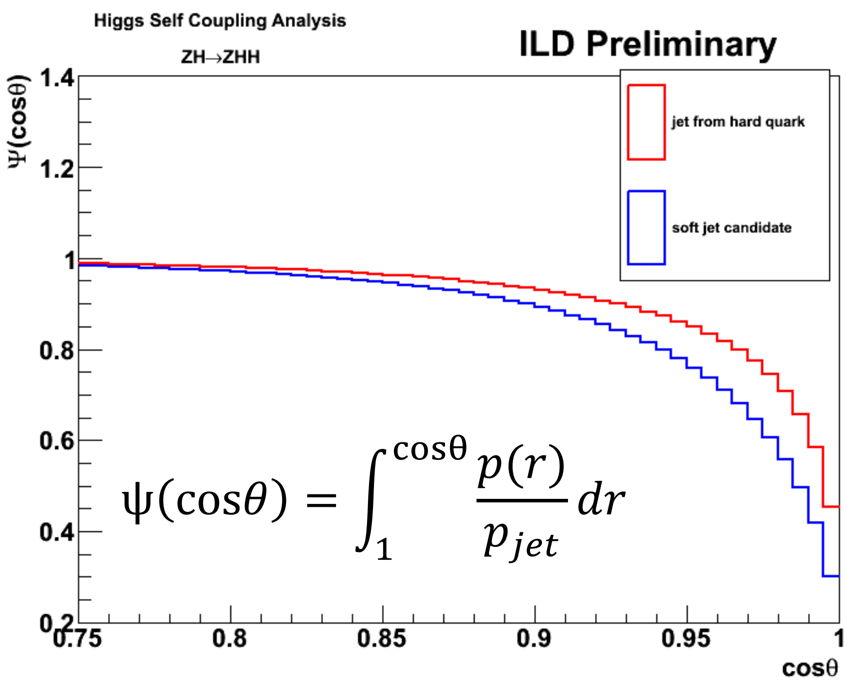
@500GeV	WW→(qq)(qq)	WW→(qq)(lv)
Z→bb	8jets	Lepton+6jets
Z→cc	8jets	Lepton+6jets
Z→ll	Dilepton+6jets	Trilepton+4jets

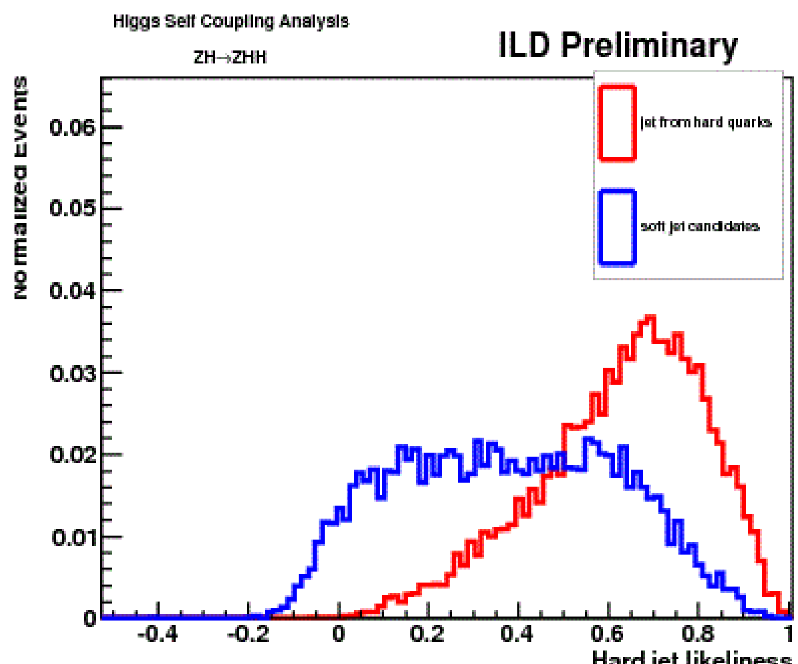
@1TeV	WW→(qq)(qq)	WW→(qq)(lv)
Z→bb	8jets	Lepton+6jets
Z→ll	Dilepton+6jets	N/A
vvHH	6jets (+missing)	N/A

- **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

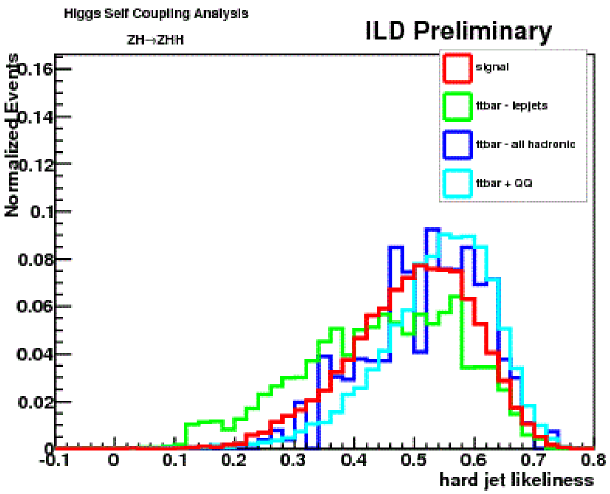
- Tracks in the gluon jets spread wider than those in quark jets(e.g. analyses on hadron collider)
  - Traditional jet shape can be a good estimator
- Using Multivariate Analysis and estimating the hard jet likeliness for each jet

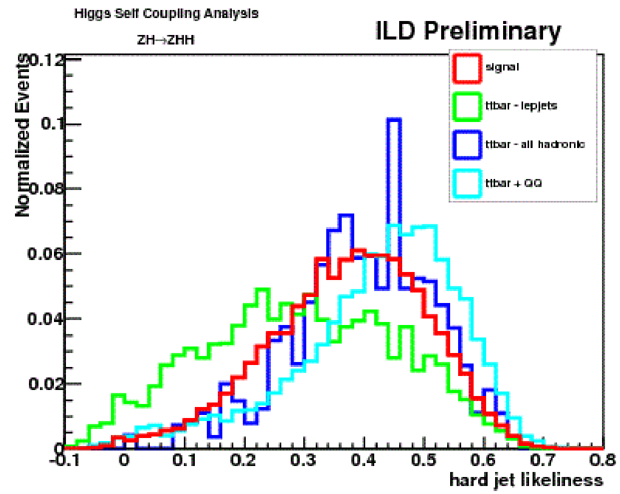




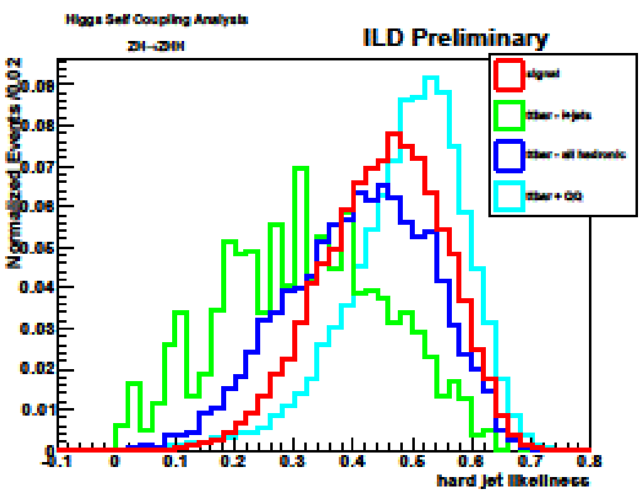
Check the performance

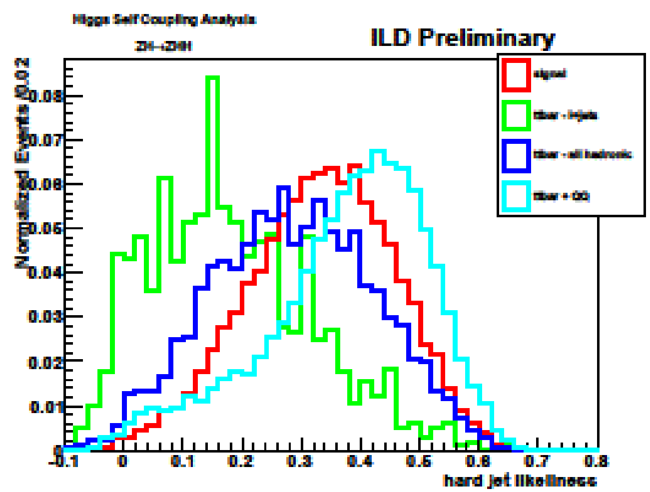
- Check the jets with small hard jet likeliness – signal vs. ttbar
- For 6jets





- For 8jets

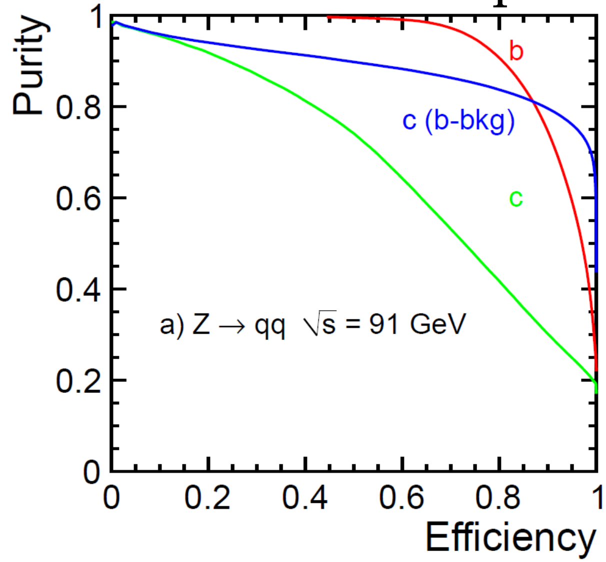


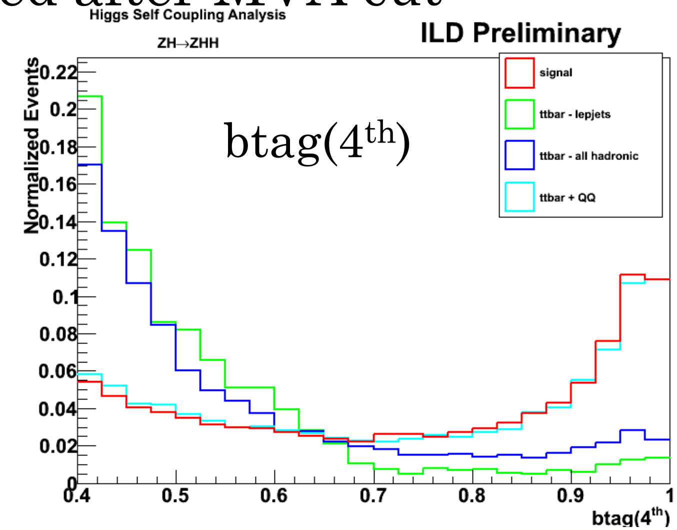


Flavor Tagging

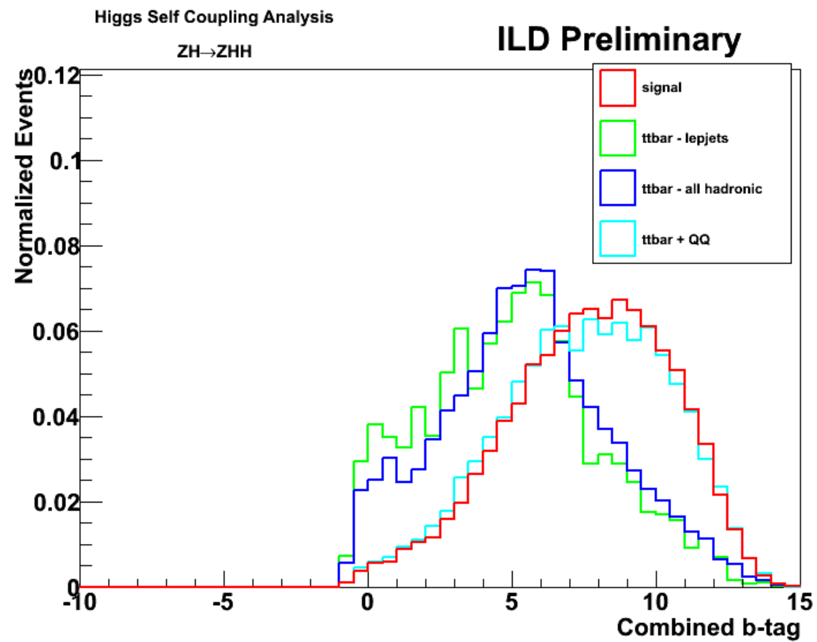
Using LCFIPlus

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





- Introduce combined b-tagging
  - After solving the jet pairing
  - $b(Combined) = \log(\frac{b_1 b_2}{(1-b_1)(1-b_2)})$
  - 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

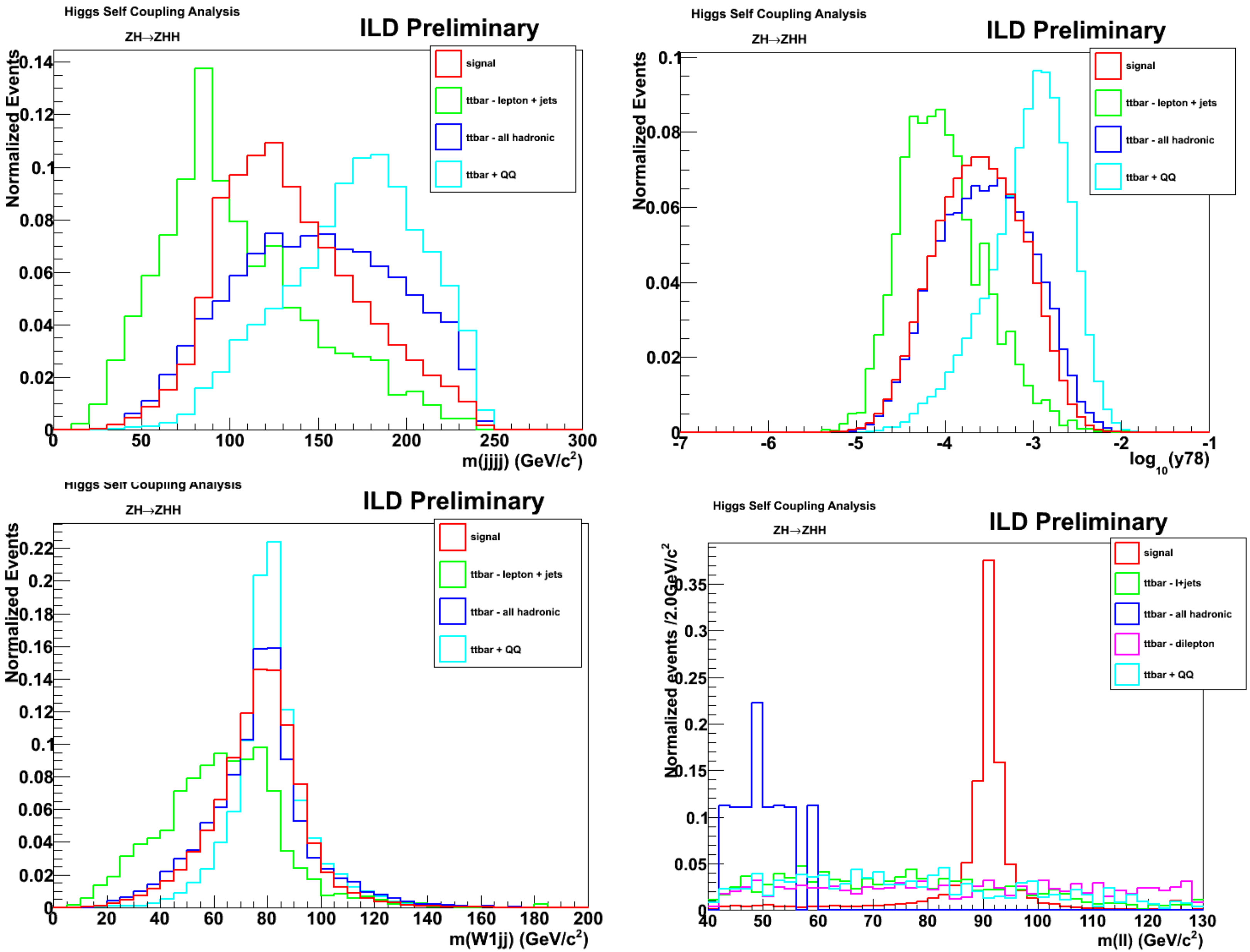
→

ttbar hadronic
- All hadronic

- Multi Variate Analysis @1TeV
  - Some cuts are implemented before MVA to tighten the input variable space – jet energy, χ^2, visible energy, (Z mass)
  - Signal vs. all the backgrounds

Some kinematic variables used for MVA

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

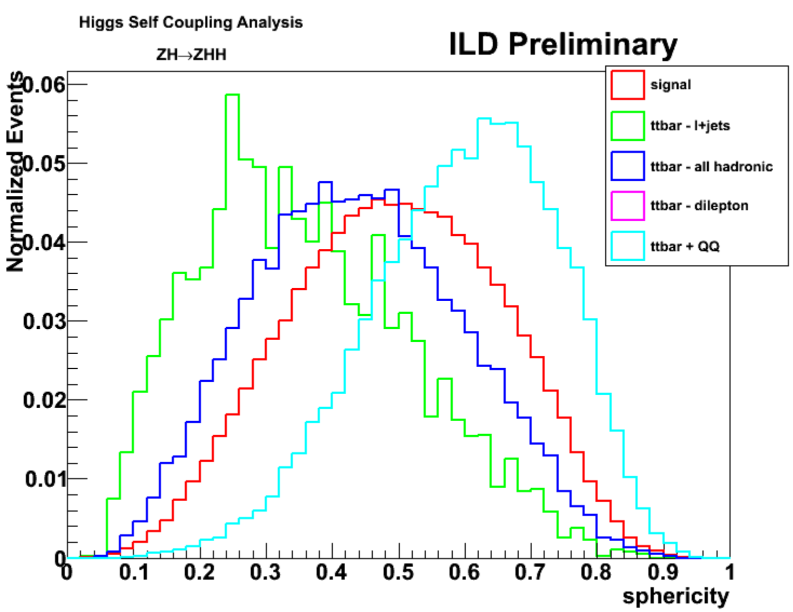


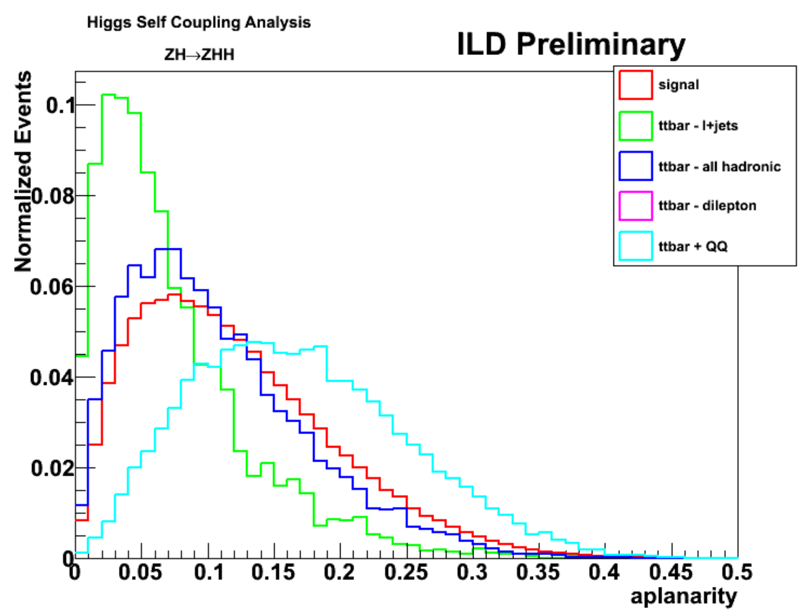
Non-simple variables used for MVA

- 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



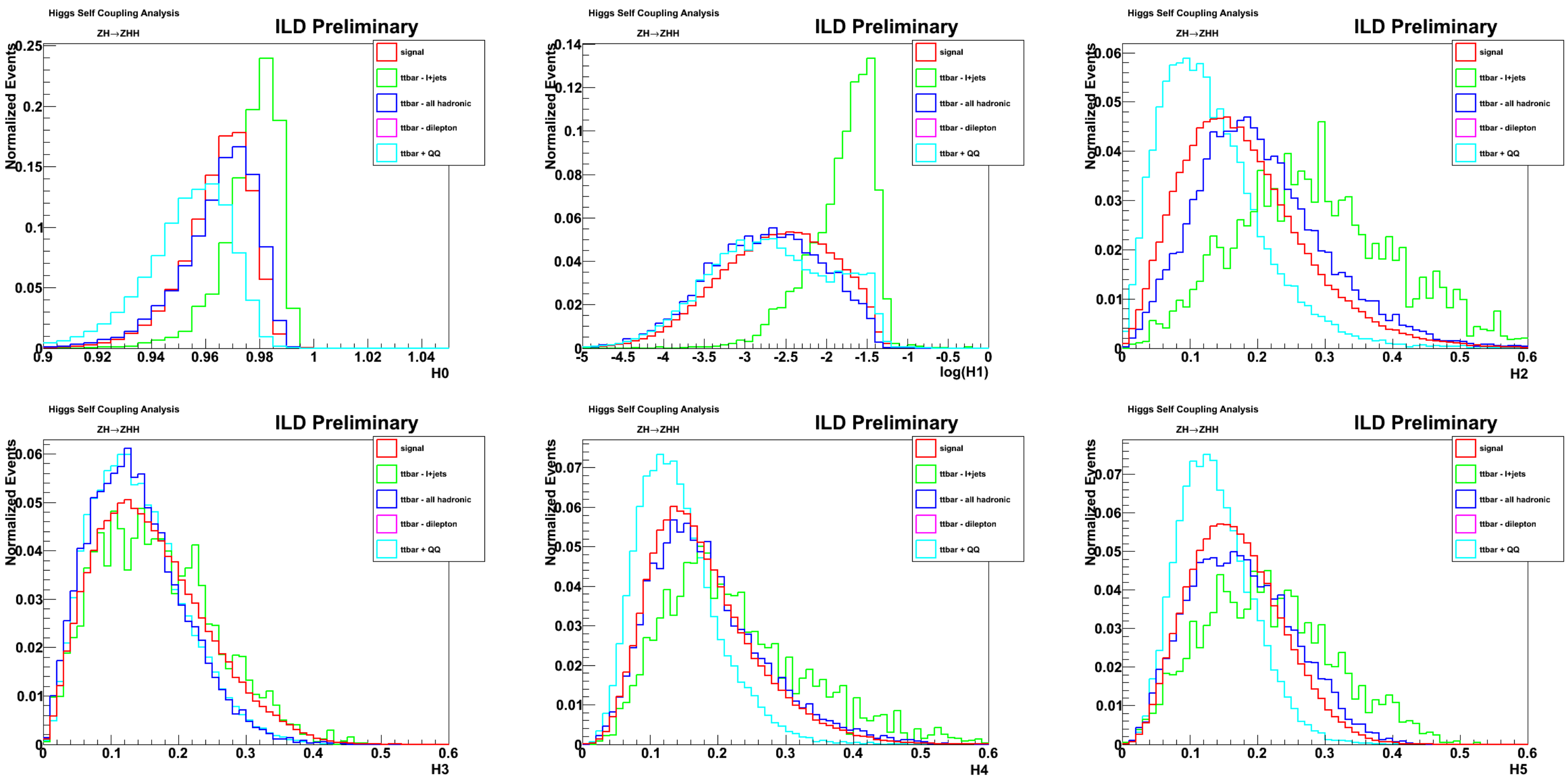


NON-SIMPLE VARIABLES USED FOR MVA

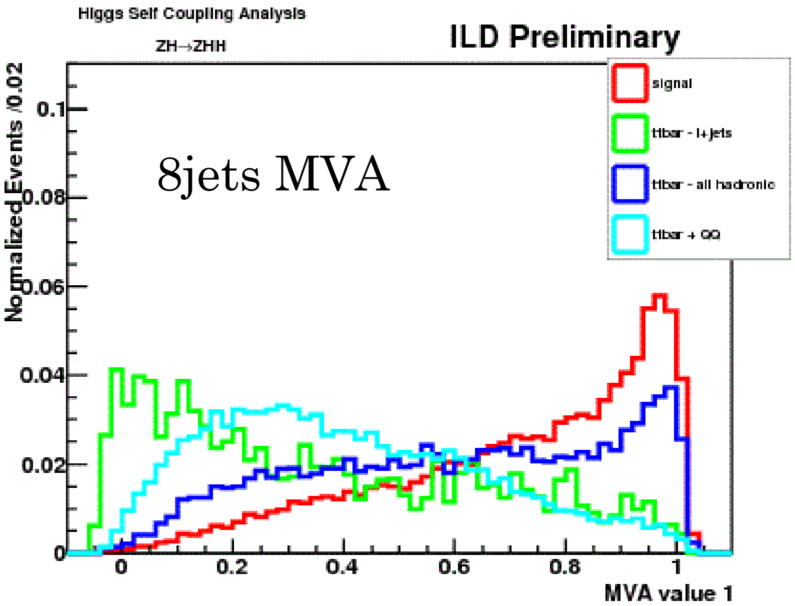
- Fox-wolfram moments

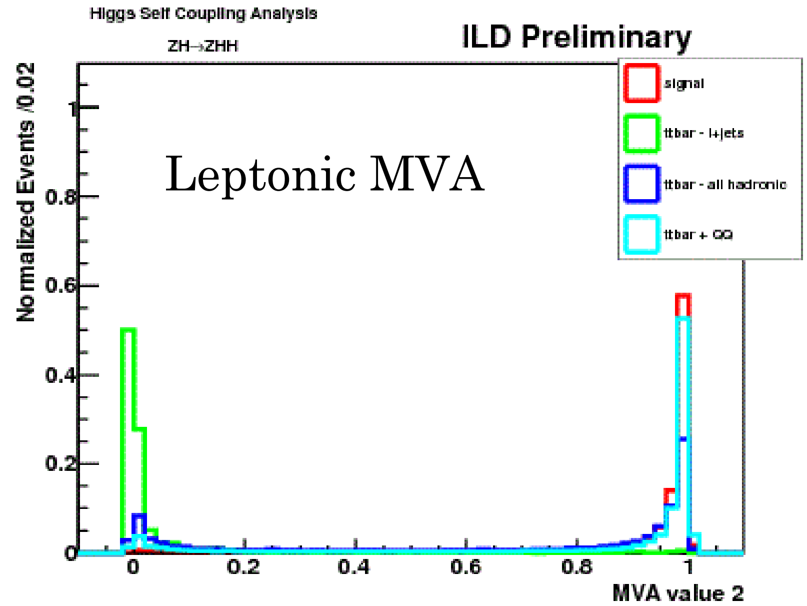
$$H_l = \sum_{i,j} \frac{|\mathbf{p}_i||\mathbf{p}_j|}{E_{\rm vis}^2} P_l(\cos\theta_{ij}) \ ,$$

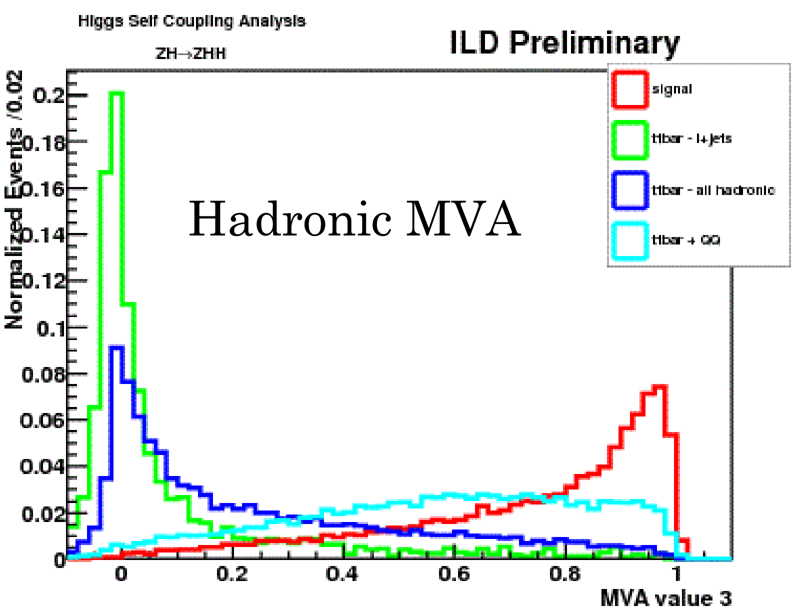
- P_l is Legendre polynomials
- Those moments characterize the structures of 2jets, 3jets, or isotropic events



MVA outputs examples(allhadronic@500GeV)







cut of MVA:

MVA8jets>0.08

MVAlep>0.02

MVAhad>0.74

Sensitivity@500GeV

- HH→(bb)(WW)
  - As mentioned, categorized with decay tipes of Z and W boson
    - Z→bb, cc or ll
  - b-tagging strategy – introduce looser b-tag category
    - 4-btag & 3-btag
  - E_{CM}=500GeV, L=2ab-1
  - **Significance ~1.91σ**

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_{CM}=1TeV, L=2ab-1
  - **Significance ~???σ**

Modes	Z decay	Signal	Background	Significance
All hadronic	Z→bb	31.54	302.62	1.73σ?
Lepton + jets	Z→bb	1.16	9.24	0.36σ
Dilepton	Z→ll	1.03	14.30	0.26σ
6jets+ Missing	No Z, vvHH	??	??	>1.10σ
Combined				**???σ**

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 **~1.91σ**
  - Total sensitivity @1TeV is **~???σ**

- **Plan:**
  - 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(EM)/(E(EM)+E(HAD))>0.90 |d0|<0.02 |z0|<0.02 Cone Energy<61.10-0.28P	E/p<min(0.5, 10.0/E) E(EM)/(E(EM)+E(HAD))<0.45 |d0|<0.02 |z0|<0.02 Cone Energy<52.45-0.28P

  - Detection efficiency of Lepton ID ~ 98.4% for lep+jets signal events

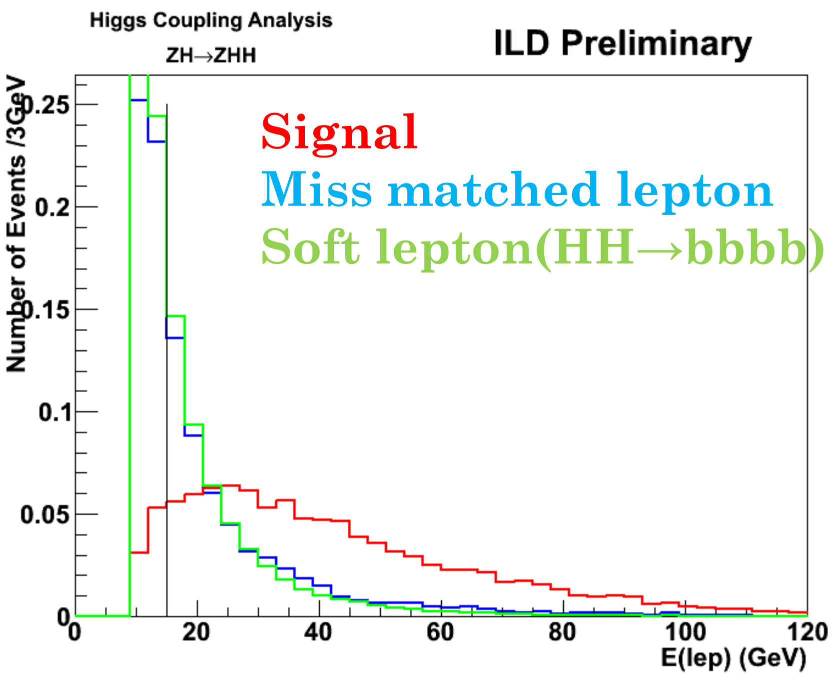
	Signal	ttbar – lep+jets	ttbar - allhad
Efficiency(%)	98.4	71.4	7.9

  - For dilepton events ~ 83.8% of signal events

	Signal	ttbar – dilepton
Efficiency(%)	83.8	84.5

EVENT SELECTION

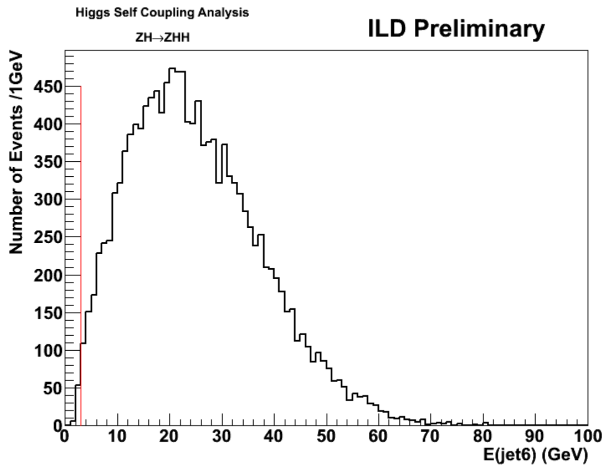
- Lepton selection
  - E(lep)>15GeV is required to suppress soft leptons
  - Dividing into 3 samples:
    - one lepton for lepton + jets
    - two leptons for dilepton → opposite charge & same flavor
    - three leptons for trilepton → looking for the lepton pair from Z
    - tight lepton veto for all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

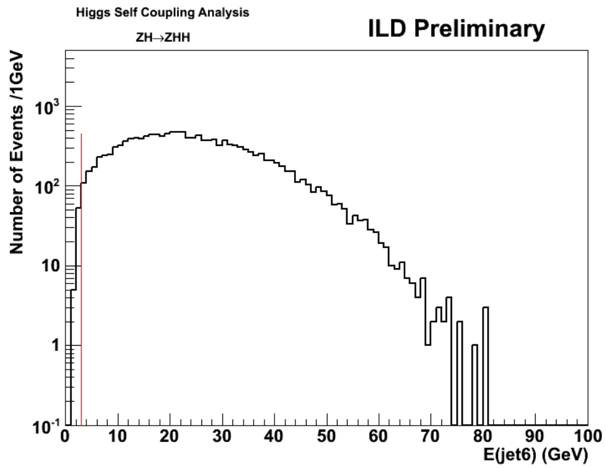


Lepton matching is required: cosθ>0.9

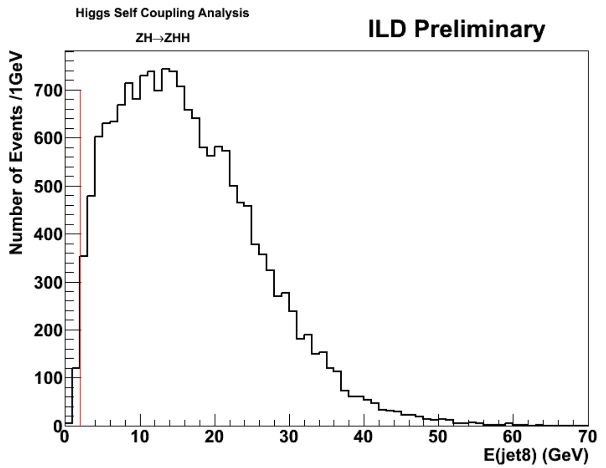
Event selection

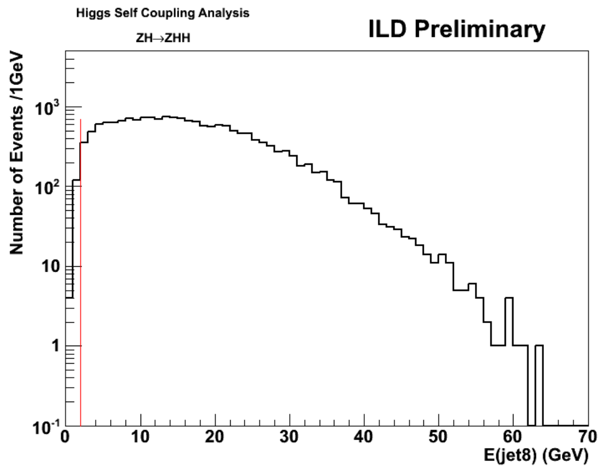
- jet selection
  - requiring 4jets, 6 jets or 8 jets using LCFIPlus & Durham
  - E(jet)>3GeV is required to care the lowest energy jet for **6 jets** case
  -





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



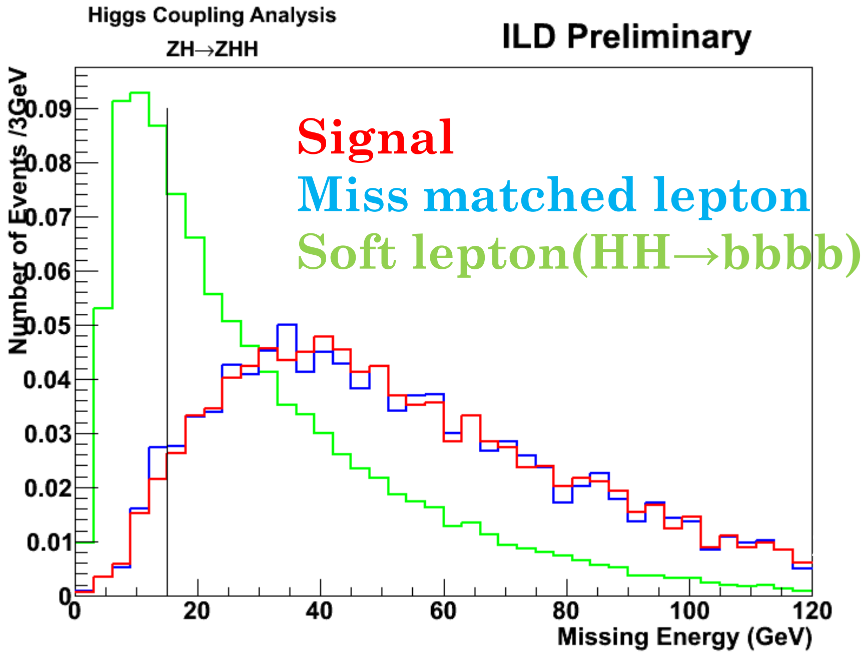


Event Selection

- 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(Miss)>15GeV/c to suppress HH→bbbb events
  - All hadronic & dilepton: P(Miss)<80 GeV/c required
  - Trilepton: P(Miss)<150GeV/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>15GeV 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

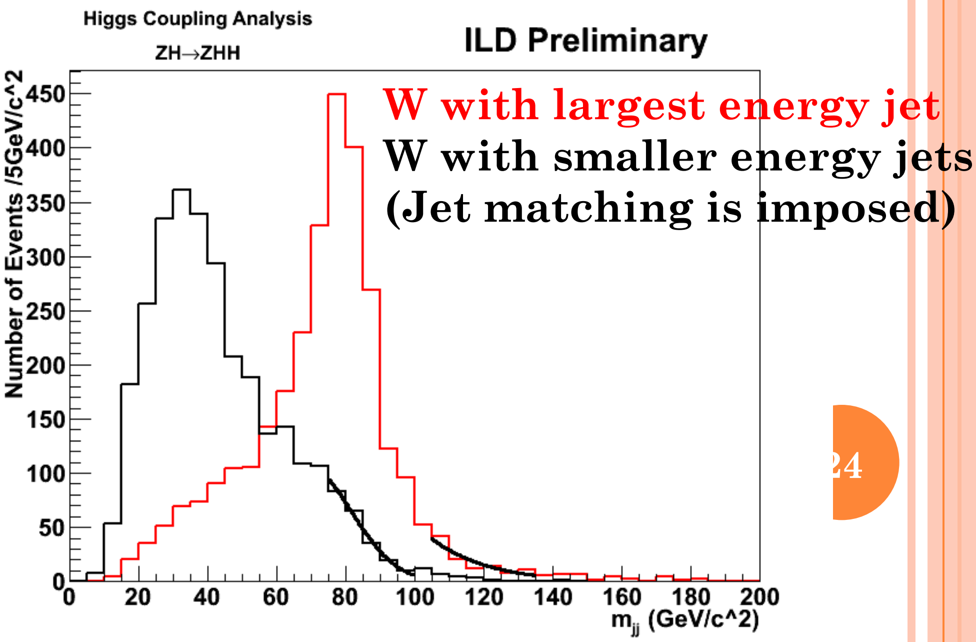
Category(Lep. Num.)	0	1	2	3
P(Miss) (GeV/c)	P<80	P>15	P<80	P<150

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:

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

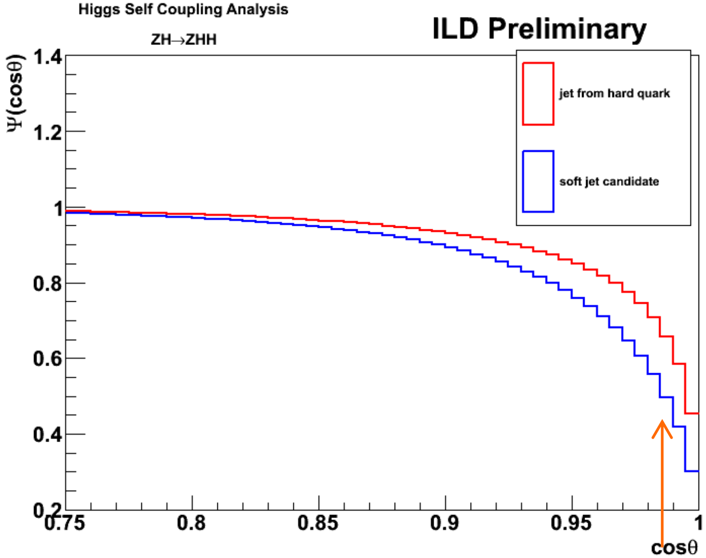
  - Light flavor jet assignment to 2 W bosons:
    - Mass constraint is imposed only to the W boson with largest energy jets
    - Breit-Wigner is assumed for W mass shape
    - $\chi^2 = -2\mathrm{Log}(\mathrm{BW}(m_{W1}|m_W, \Gamma_W))$

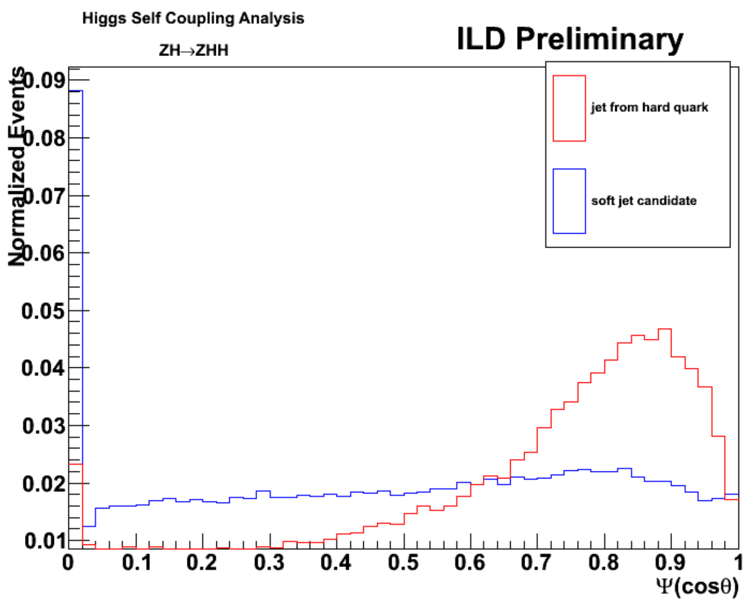


SOFT JET FINDING

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

$$\psi(\cos\theta) = \int_{1}^{\cos\theta} \frac{p(r)}{p_{jet}} dr$$

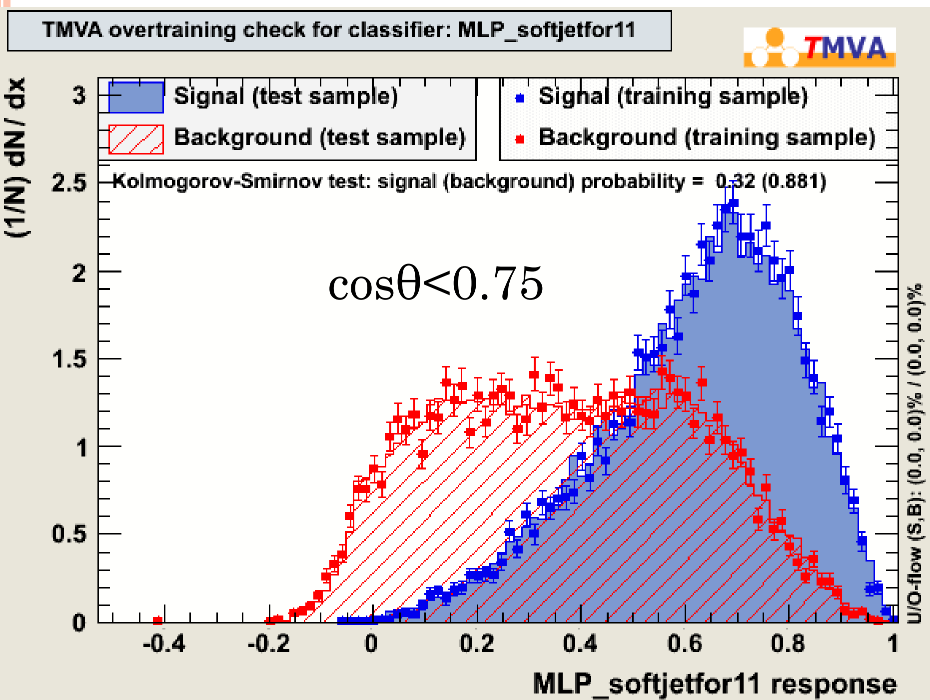


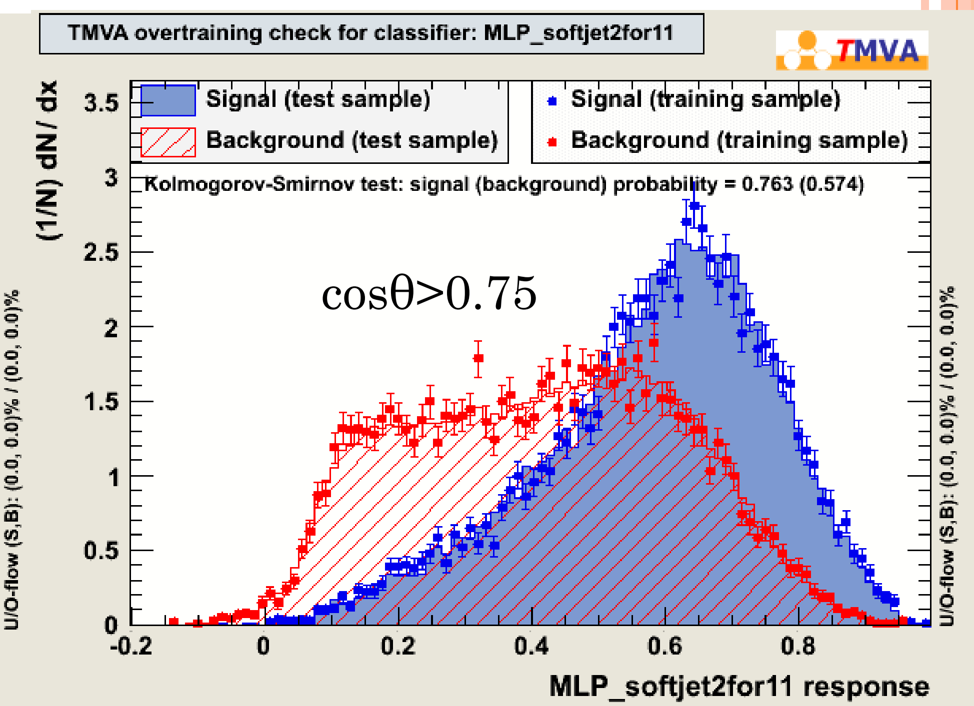


Soft jet finding

- 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
$\chi2$	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