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

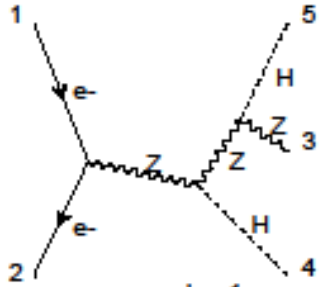
Quartic coupling
→difficult to measure

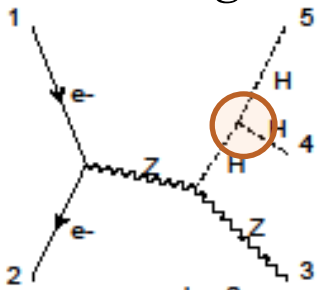
$$SM: \quad \lambda = \frac{m_H^2}{2v^2} \qquad v \sim 246 GeV$$

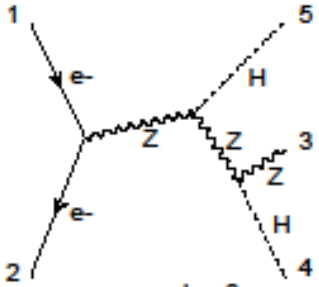
- Observing two Higgs bosons in the event is the only way to measure the self coupling
- Accurate test of the coupling may lead to the extended nature of Higgs sector → may go to new physics
- Our goal is to observe and measure the Higgs self coupling first

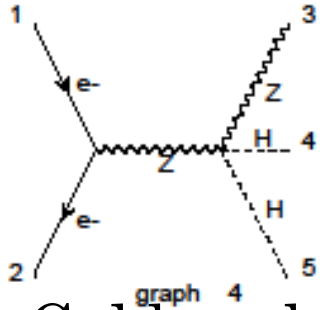
Signal Events

- Signal: $e^+e^- \rightarrow Z^* \rightarrow ZH \rightarrow ZHH$ is used for the analysis
  - Cross section is largest@500GeV for the self coupling analysis



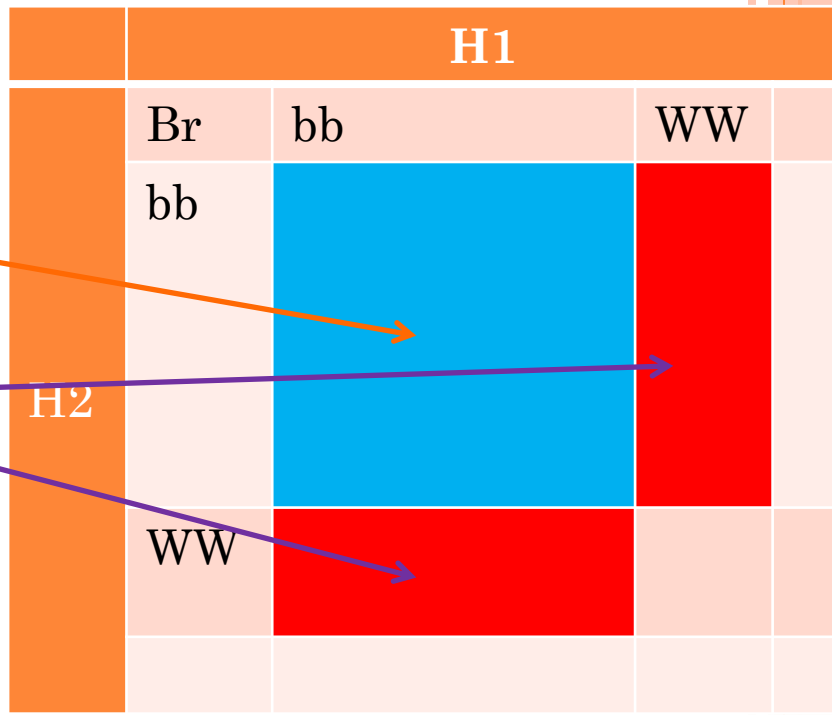






Signal: 2
Irreducible B.G.: 1, 3,4

- Golden channel: Z(bb)(bb)
  - b-tagging is important
- Requirement of **H→WW*** decay
  - Contribution of the total sensitivity
  - Need to reduce the backgrounds using kinematics of the events



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

- Simulation
  - Polarization: (e, p)=(-0.8, +0.3)
  - Higgs mass is set @125GeV/c^2
  - Using the full simulation with DBD detector configuration

process	σ(fb)
Signal(inclusive)	0.2
ttbar & ZWW	581.8
ttbar + QQ	0.83
ttbar + Z	0.98
ttbar + H	0.14
ZZ + H	0.77
ZZZ	1.83

Analysis strategy for HH→(bb)(WW)

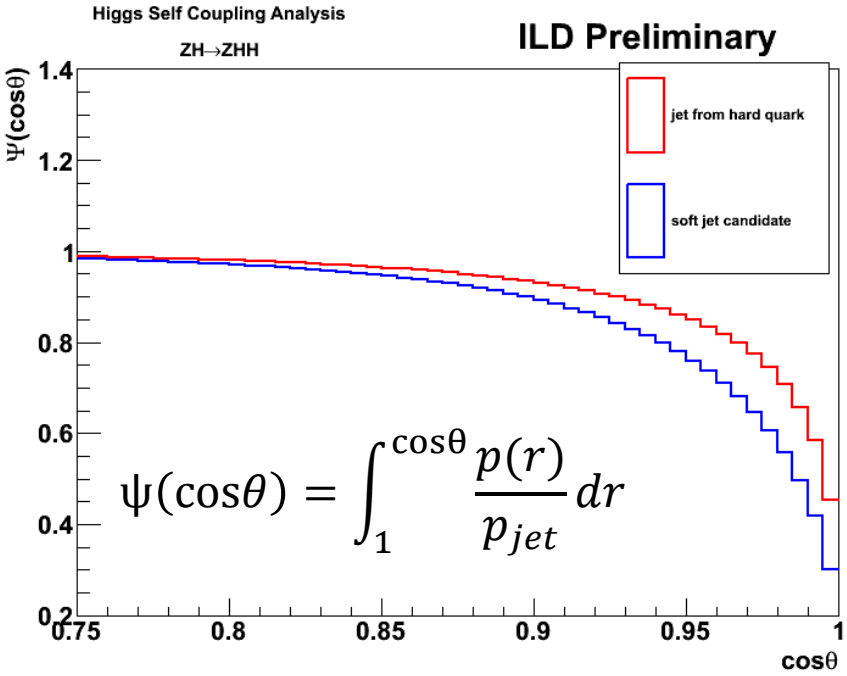
- Classify the events with Z and W decays:

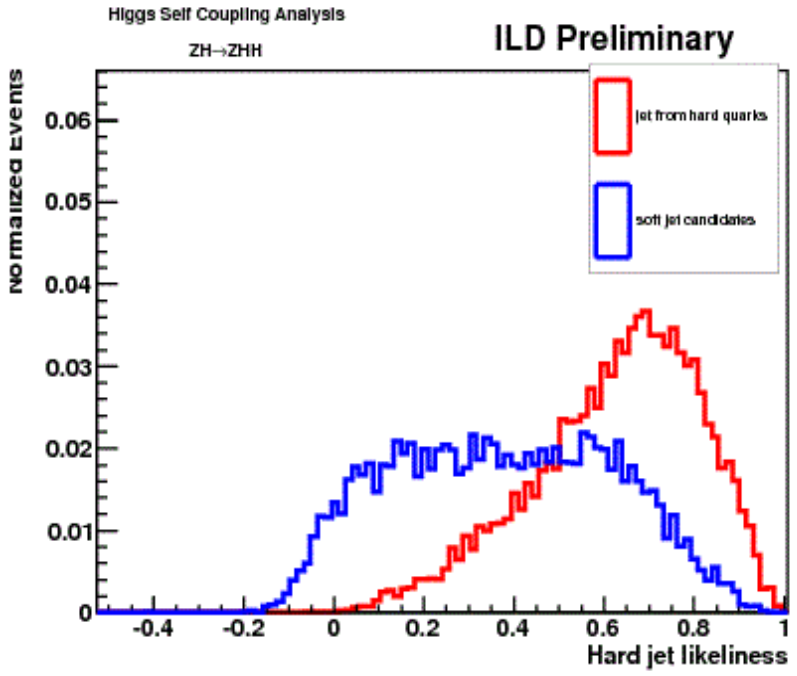
	WW→(qq)(qq)	WW→(qq)(lv)
Z→bb	8jets	Lepton+6jets
Z→cc	8jets	Lepton+6jets
Z→ll	Dilepton+6jets	Trilepton+4jets

- **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

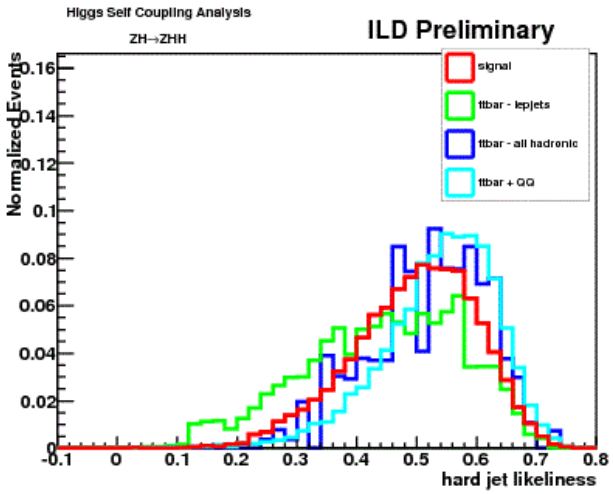
- Tracks in the gluon jets spread wider than those in quark jets(e.g. analyses on hadron collider)
  - Traditional jet shape can be a good estimator
- Using Multivariate Analysis and estimating the hard jet likeliness for each jet

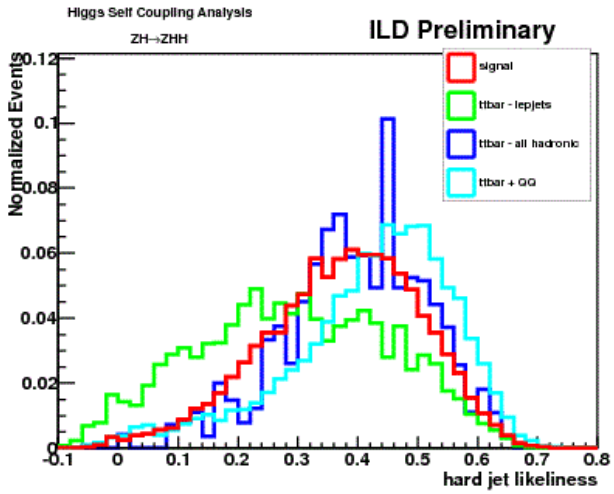




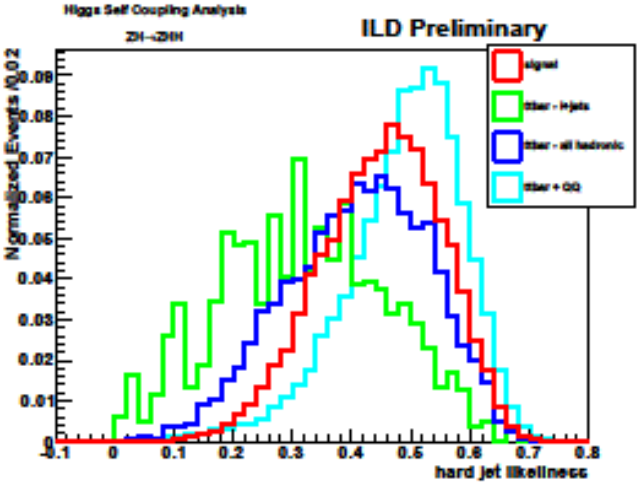
CHECK THE PERFORMANCE

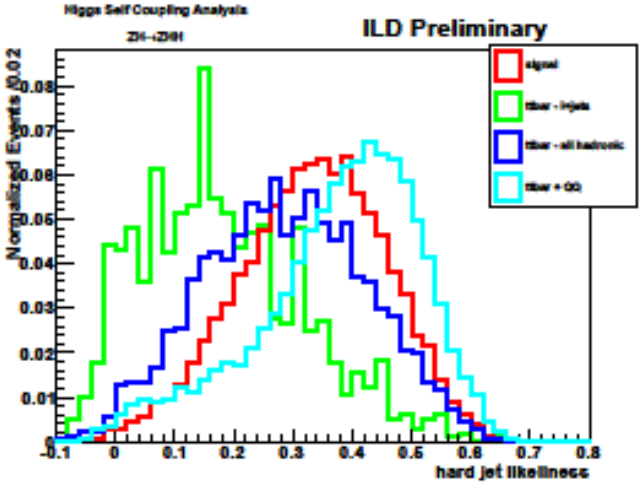
- Check the jets with small hard jet likeliness – signal vs. ttbar
- For 6jets





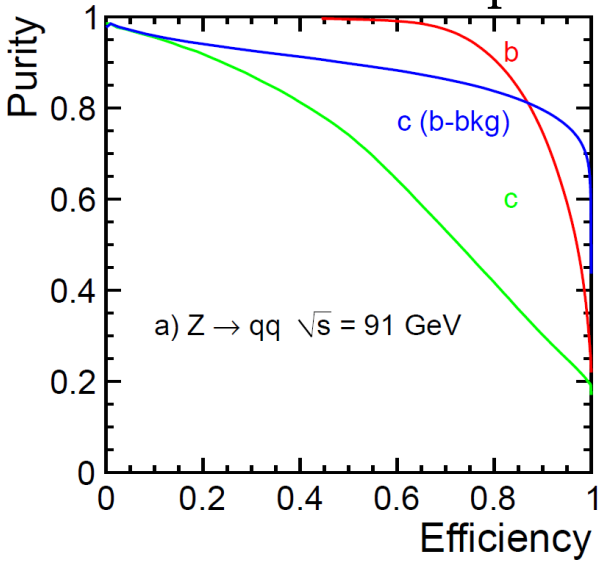
- For 8iets

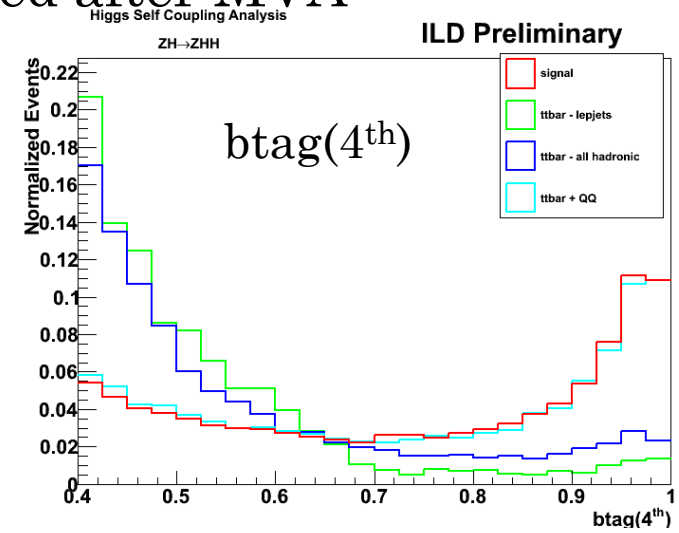




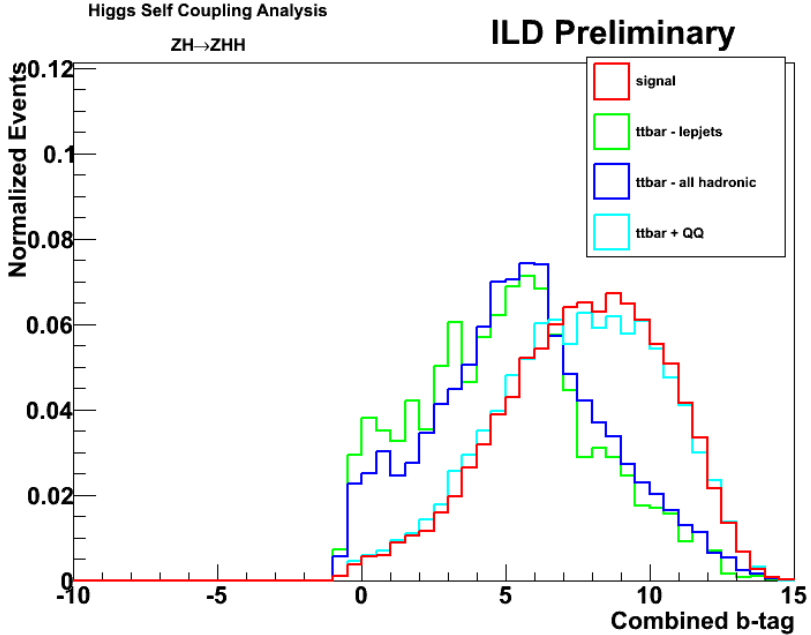
Flavor Tagging
Using LCFIPlus

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



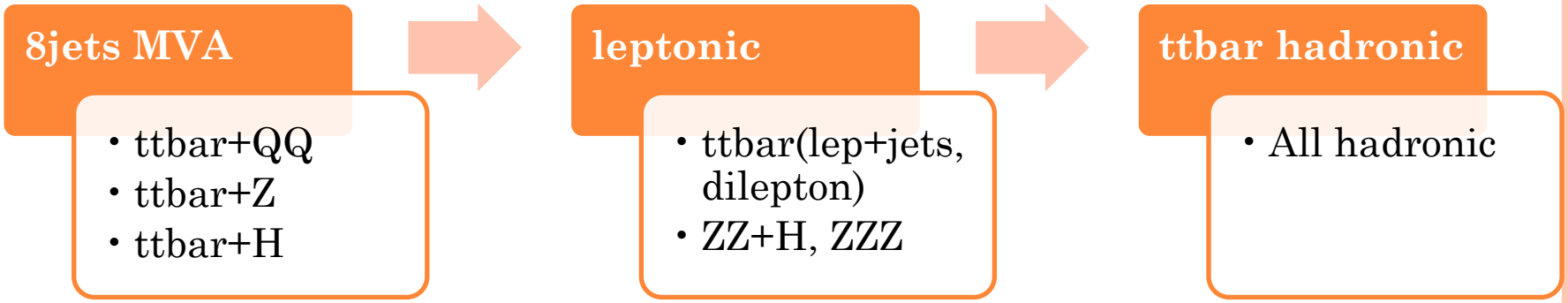


- Introduce combined b-tagging
  - After solving the jet pairing
  - $b(Combined) = \frac{b_1 b_2}{(1-b_1)(1-b_2)}$
  - Use as an input variable for MVA



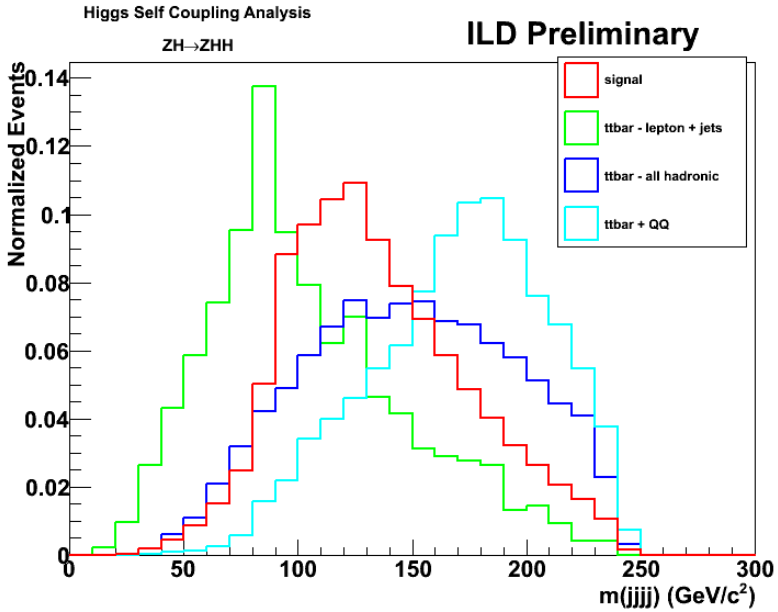
Background rejection

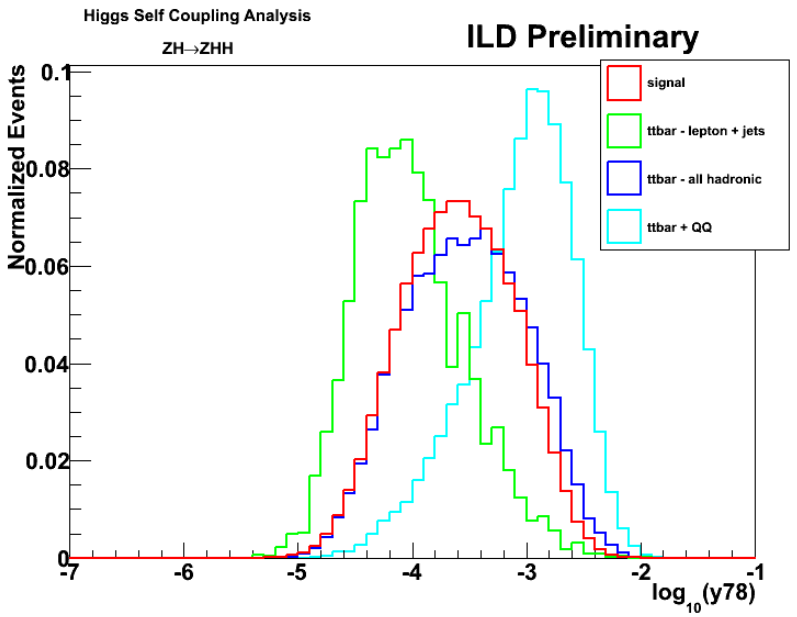
- Using Multi Variate Analysis
  - Some cuts are implemented before MVA to tighten the input variable space – jet energy, χ^2, visible energy, (Z mass)
  - Background rejection strategy : rejecting small backgrounds first and then rejecting main background
    - Tighten the variable space when rejecting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

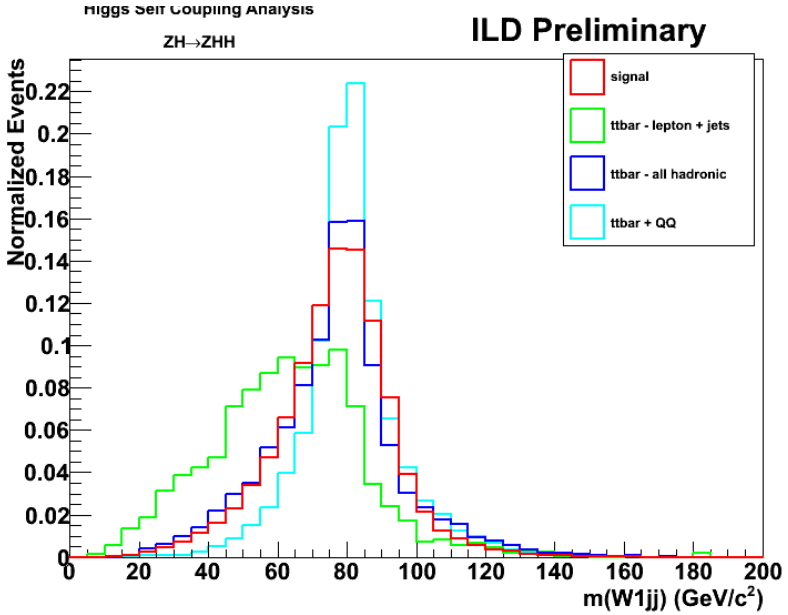


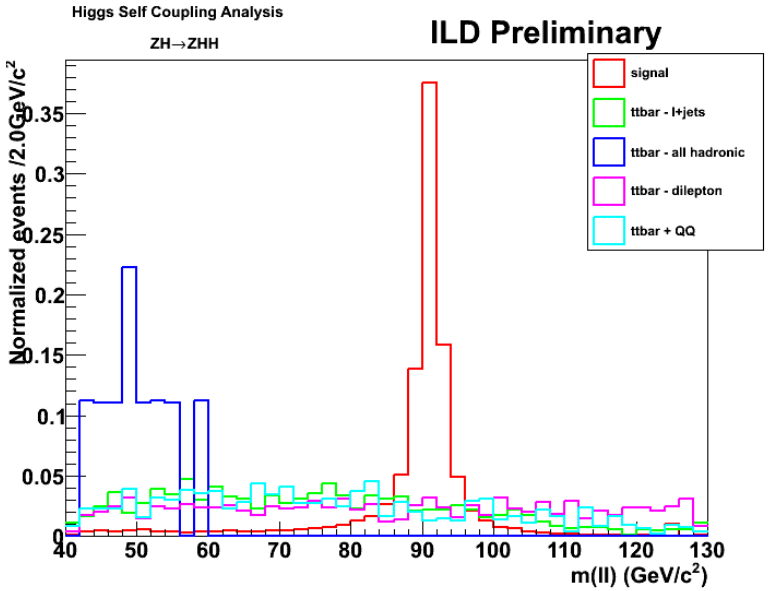
Some kinematic variables used for MVA

Very powerful variable: m(jjjj), m(lvjj)







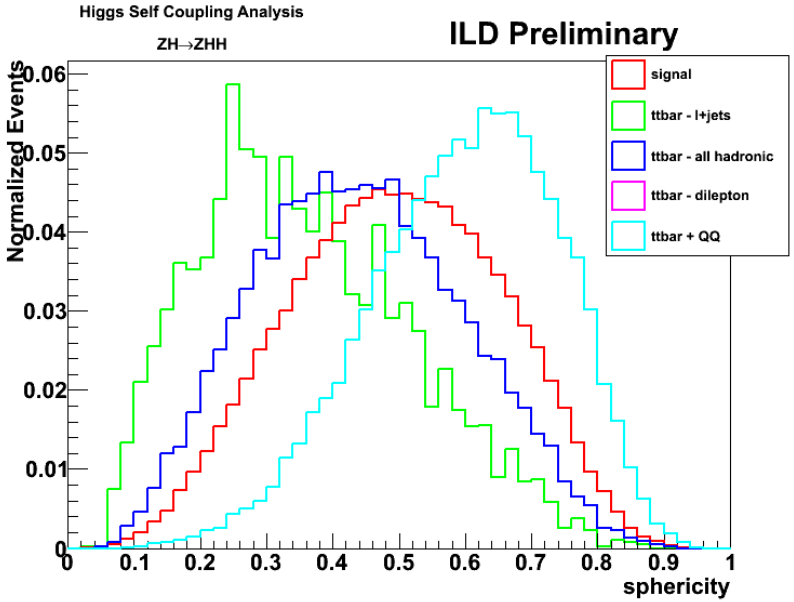


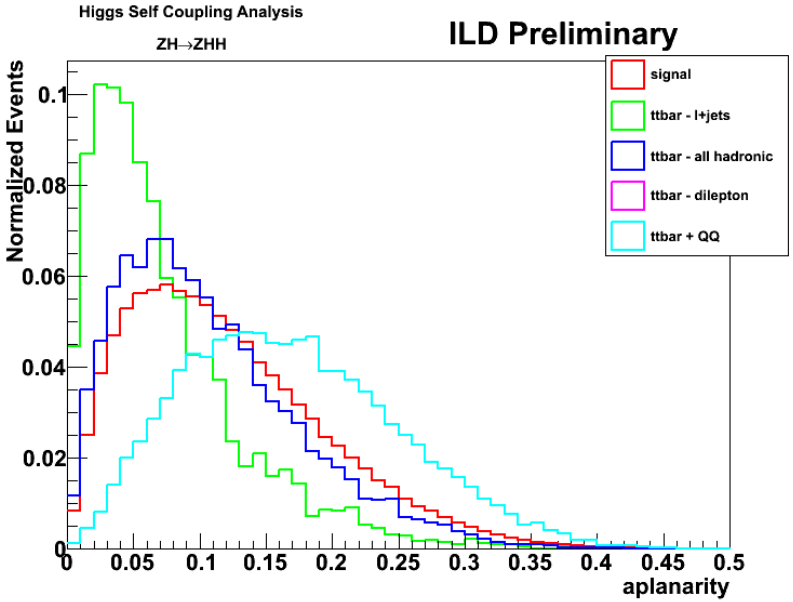
Non-simple variables used for MVA

- 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



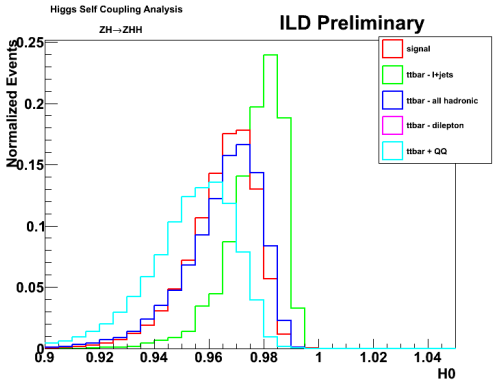


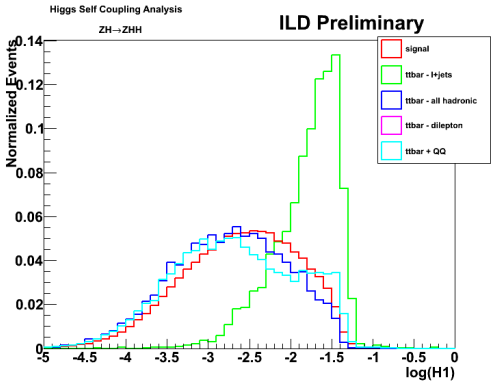
Non-simple variables used for MVA

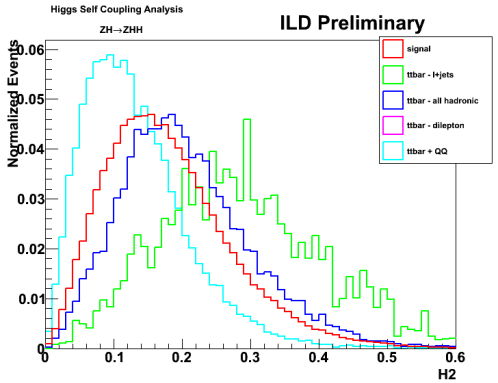
- Fox-wolfram moments

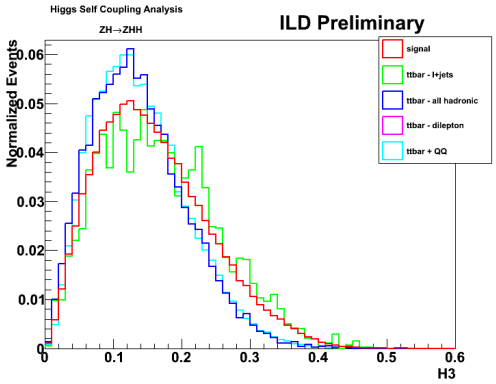
$$H_l = \sum_{i,j} \frac{|\mathbf{p}_i||\mathbf{p}_j|}{E_{\mathrm{vis}}^2} P_l(\cos\theta_{ij}) \ ,$$

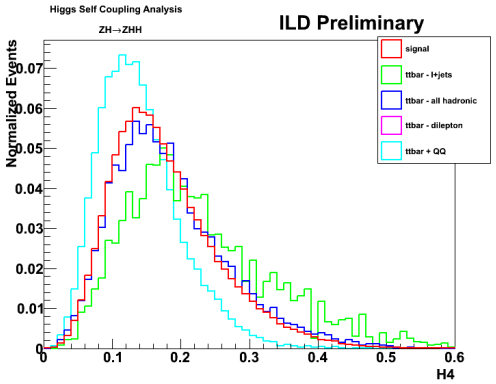
  - P_l is Legendre polynomials
  - Those moments characterize the structures of 2jets, 3jets, or isotropic events

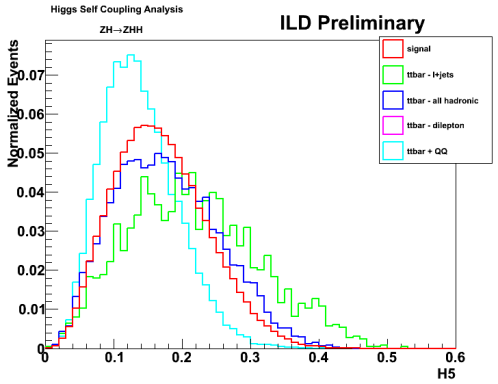




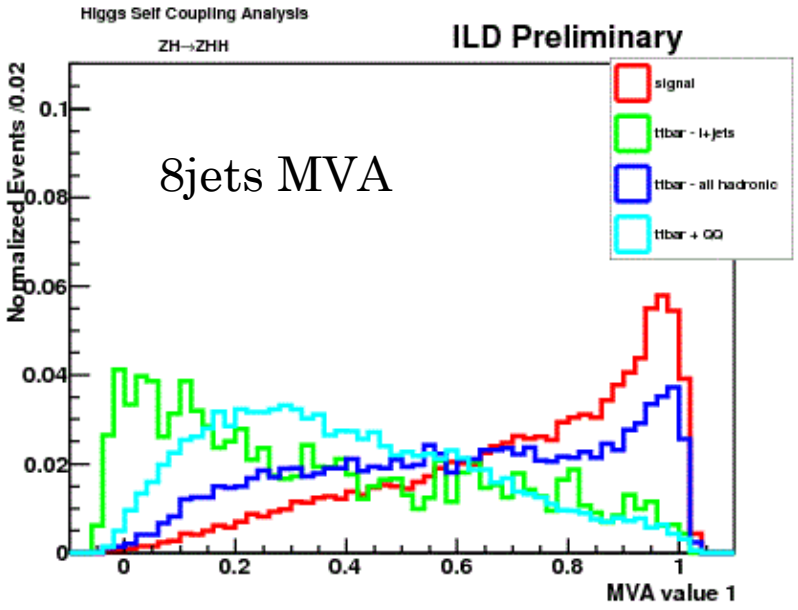




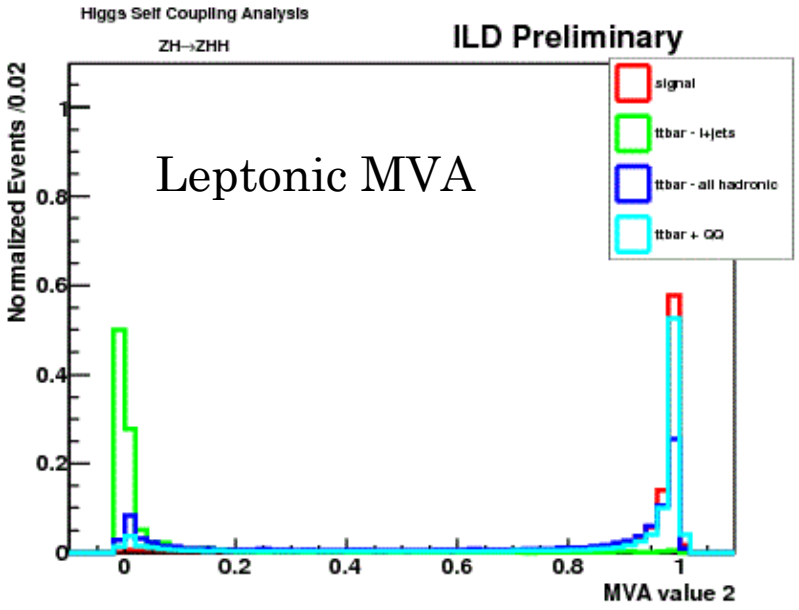




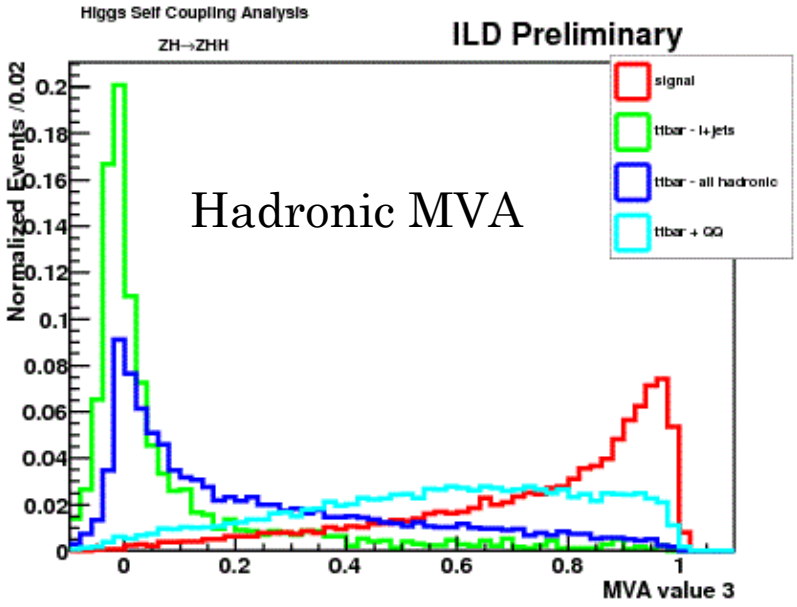
MVA OUTPUTS EXAMPLES(ALLHADRONIC)



8jets MVA



Leptonic MVA



Hadronic MVA

cut of MVA:

MVA8jets>0.08

MVAlep>0.02

MVAhad>0.74

Sensitivity

- 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 Z→cc	4btag 3btag	15.20 19.43 11.29	87.52 3099.49 366.13	1.50σ 0.35σ 0.58σ
Lepton + jets	Z→bb Z→cc		1.65 1.50	17.62 819.61	0.38σ 0.05σ
Dilepton	Z→ll		2.24	8.44	0.69σ
Trilepton	Z→ll		1.05	2.60	0.55σ
Combined					**1.91σ**

Summary and plan

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

- **Plan:**
  - Optimize b-tagging strategy
    - Fewer number of b-tagging sample
  - Analysis@1TeV
  - Improvement of basic components for the analysis
    - Lepton ID
    - b-tagging
    - Jet energy resolution
    - 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

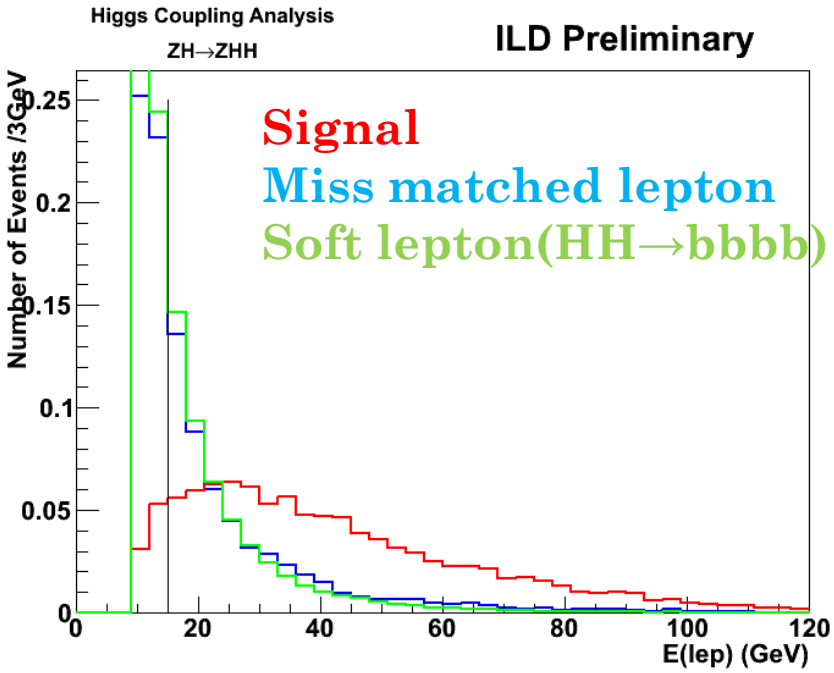
	Signal	ttbar – lep+jets	ttbar - allhad
Efficiency(%)	98.4	71.4	7.9

  - For dilepton events ~ 83.8% of signal events

	Signal	ttbar – dilepton
Efficiency(%)	83.8	84.5

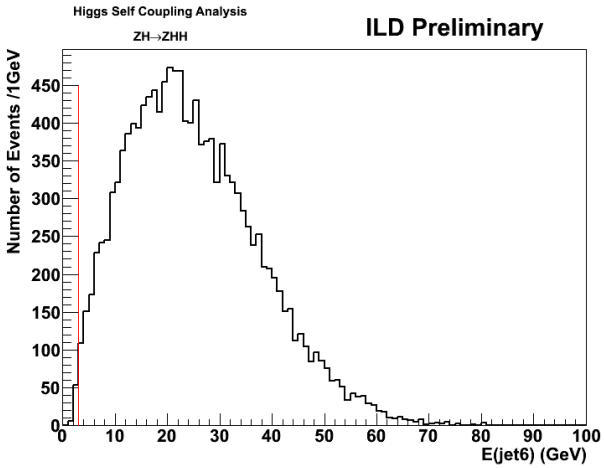
Event selection

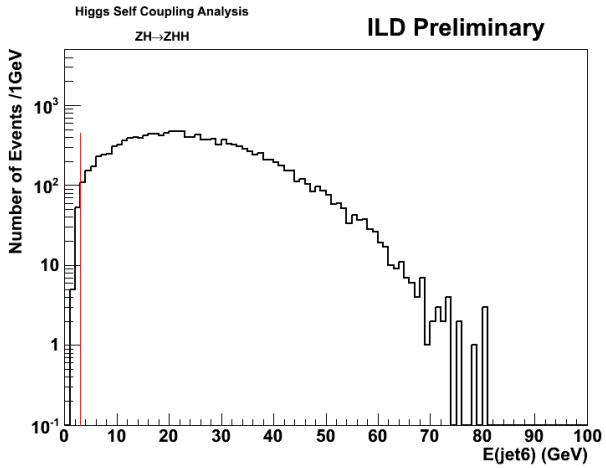
- Lepton selection
  - E(lep)>15GeV is required to suppress soft leptons
  - Dividing into 3 samples:
    - one lepton for lepton + jets
    - two leptons for dilepton → opposite charge & same flavor
    - three leptons for trilepton → looking for the lepton pair from Z
    - tight lepton veto for all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



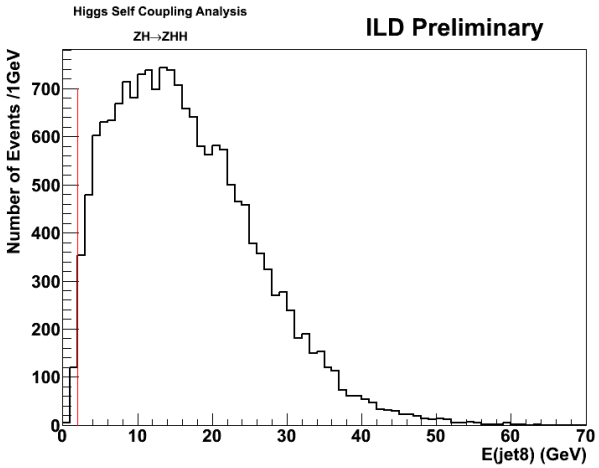
Lepton matching is required:
cosθ>0.9

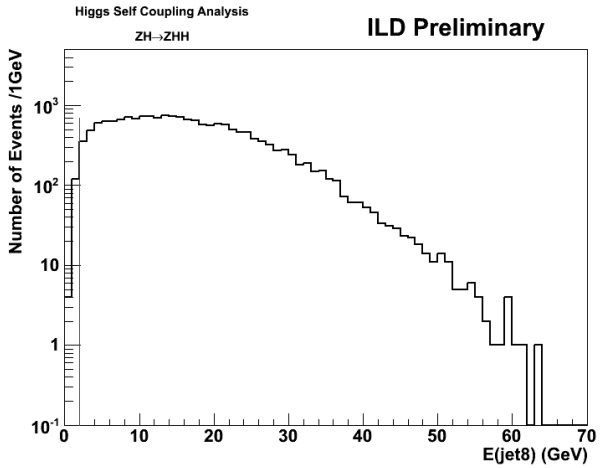
Event selection

- 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



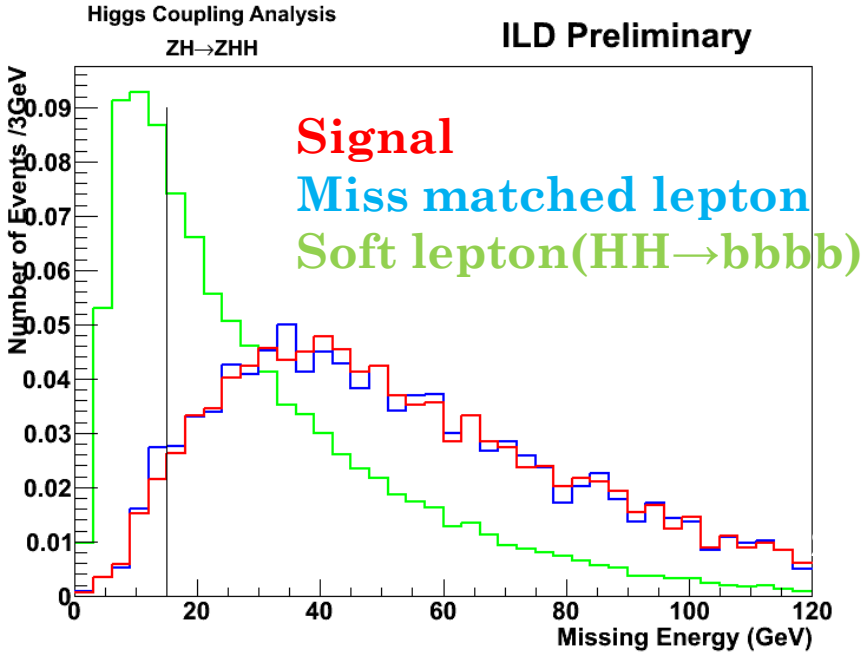


Event Selection

- 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

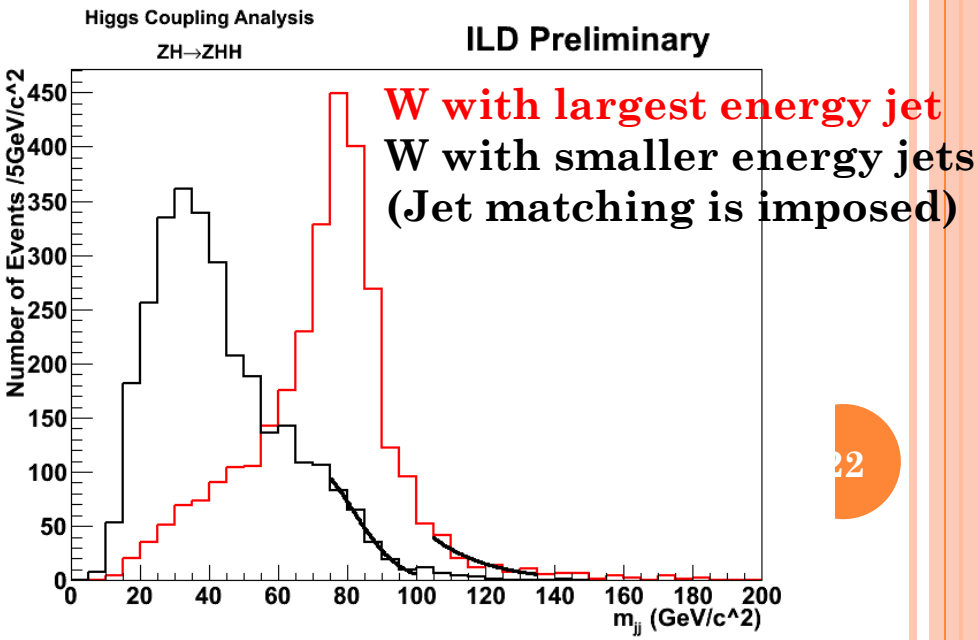
Category(Lep. Num.)	0	1	2	3
P(Miss) (GeV/c)	P<80	P>15	P<80	P<150

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:

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

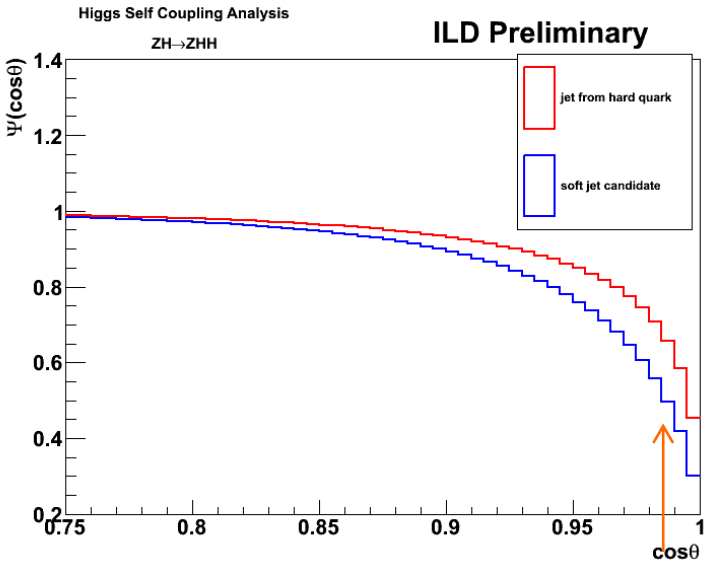
  - Light flavor jet assignment to 2 W bosons:
    - Mass constraint is imposed only to the W boson with largest energy jets
    - Breit-Wigner is assumed for W mass shape
    - $\chi^2 = -2\mathrm{Log}(\mathrm{BW}(m_{W1}|m_W, \Gamma_W))$

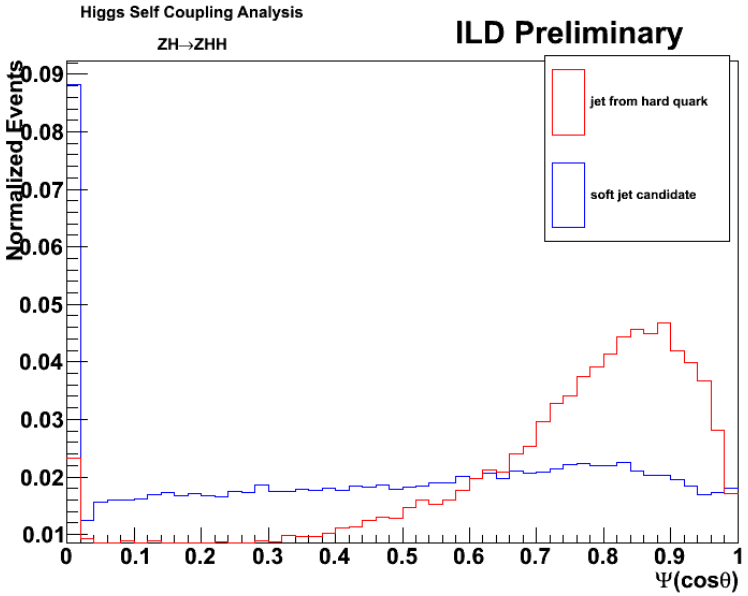


Soft jet finding

- 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

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

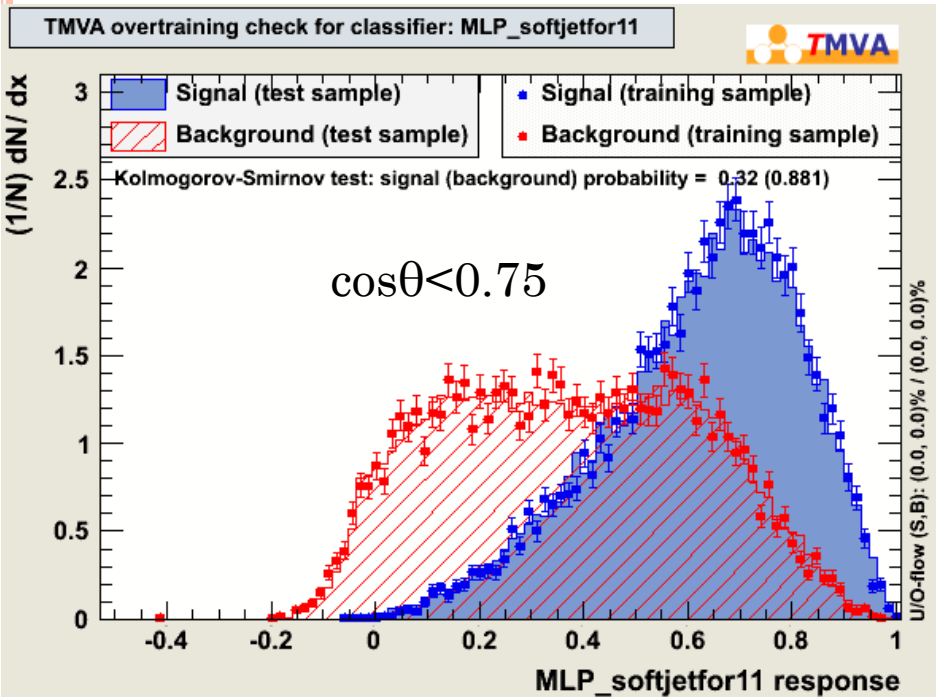


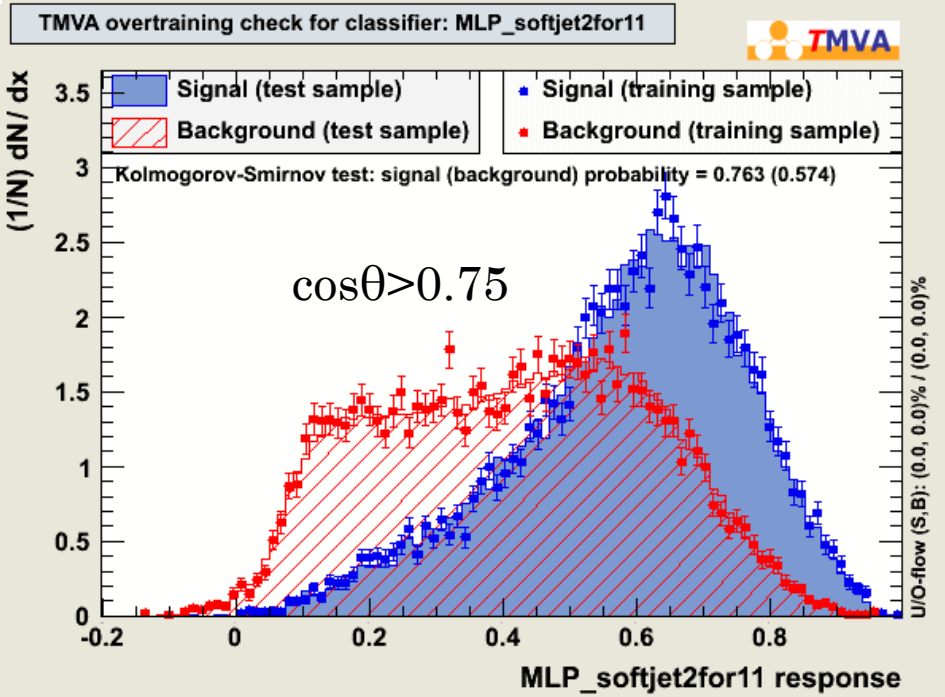


Soft jet finding

- 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
χ2	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