Sensitivity to the Higgs self coupling using full simulation of ZHH at ILD

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International Linear Collider

The International Linear Collider is the next generation precision machine:

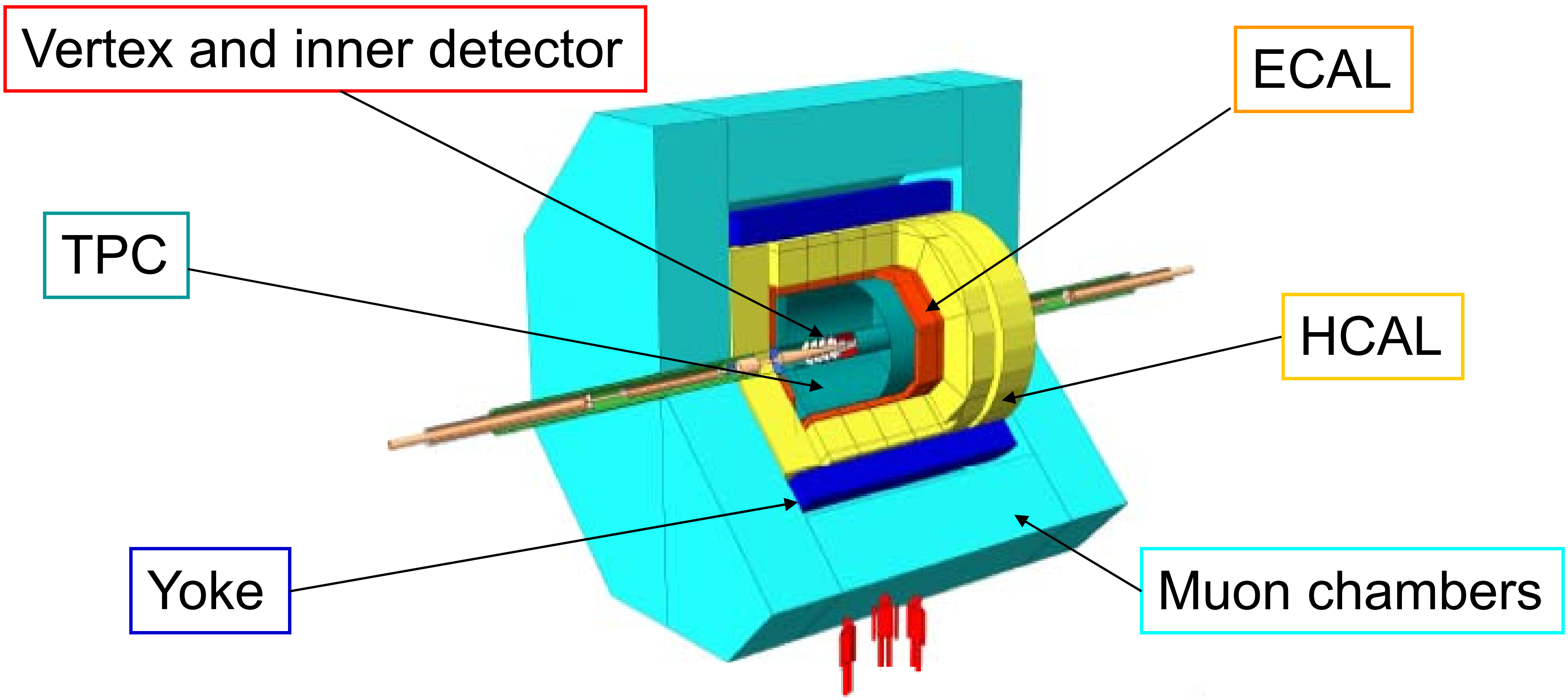
The machine is designed to be 30 km long and will use superconducting RF cavities to accelerate polarized electrons and positrons up to 500 GeV for collisions from 90 GeV up to 1 TeV.

The Goal is to perform high precision SM and beyond-SM measurements:

- SM precision measurements, top physics
- BR, couplings to particle and self coupling of the Higgs
- SUSY spectroscopy
- Extra dimensions
- …

Detector at ILC

The International Large Detector (ILD) is the European-Japanese concept for a Linear Collider general purpose detector.



The design of the detector is still to be optimized, I am part of the optimization group

Particle Flow concept

Using high granularity calorimeters it should be possible to separate each cluster in a jet.

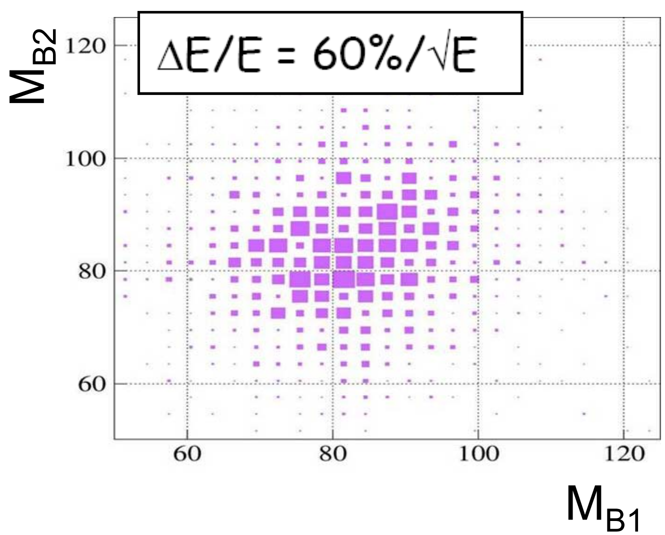
The energy of charged particles is measured through the high resolution of momentum

The calorimeters would measure only the energy of the neutral particles

The goal is to achieve a jet energy resolution of 30%/√E

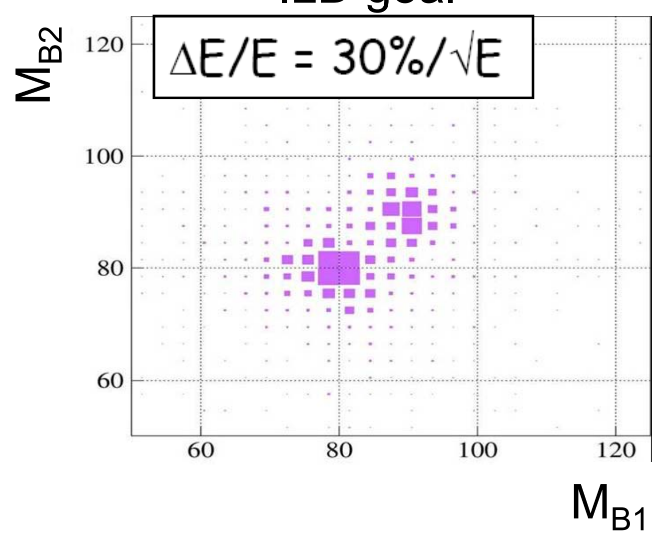
Gain of a factor 2 in required integrated luminosity

LEP



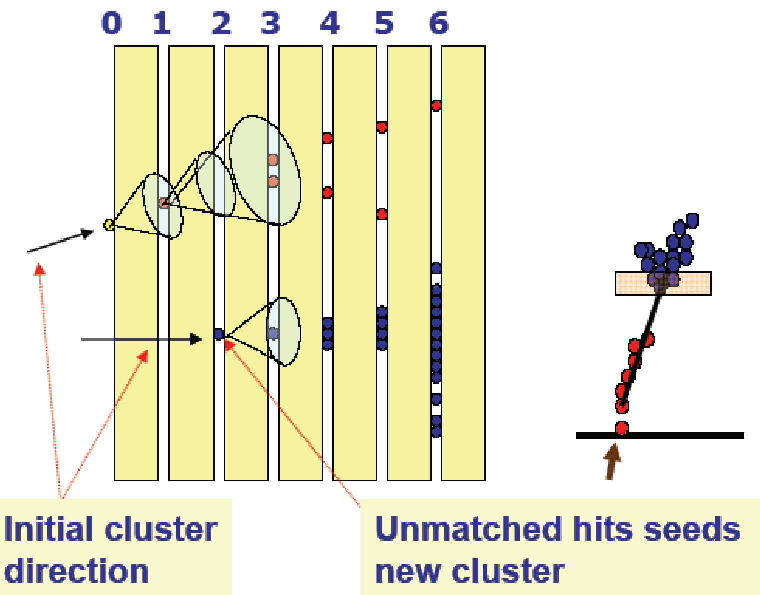
WW/ZZ separation

ILD goal

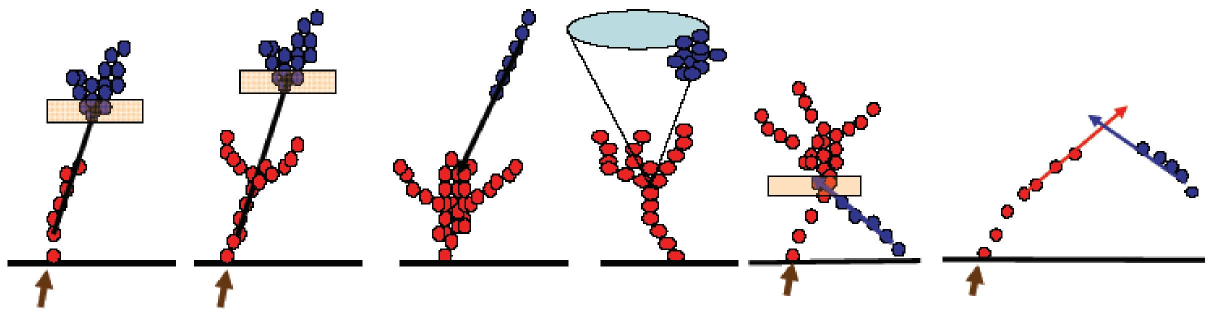


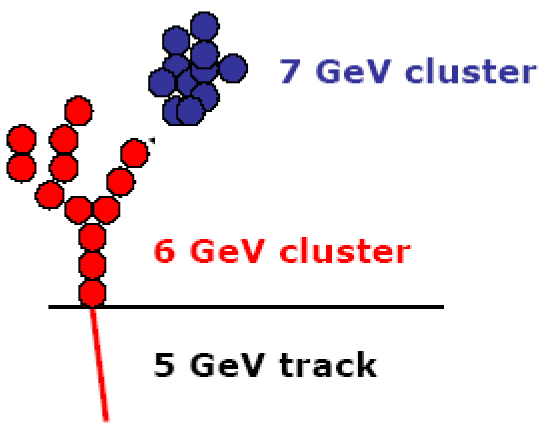
Particle Flow Algorithm

Pandora PFA by M. Thomson



Cluster association





PandoraPFA v02-01

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	0.235	3.5 %
100 GeV	0.306	3.1 %
180 GeV	0.427	3.2 %
250 GeV	0.565	3.6 %

If does not work, RECLUSTER!

ZHH physics

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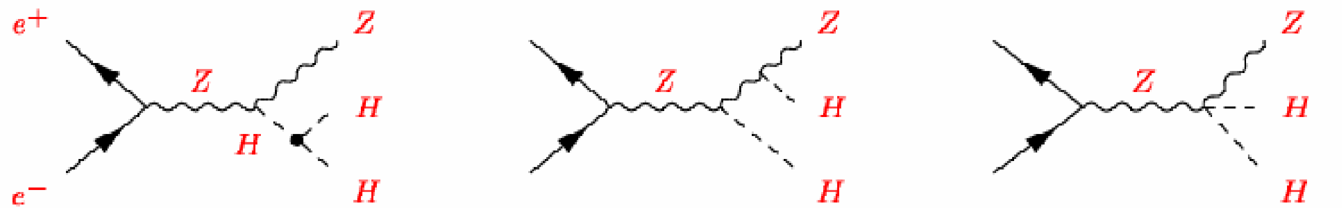
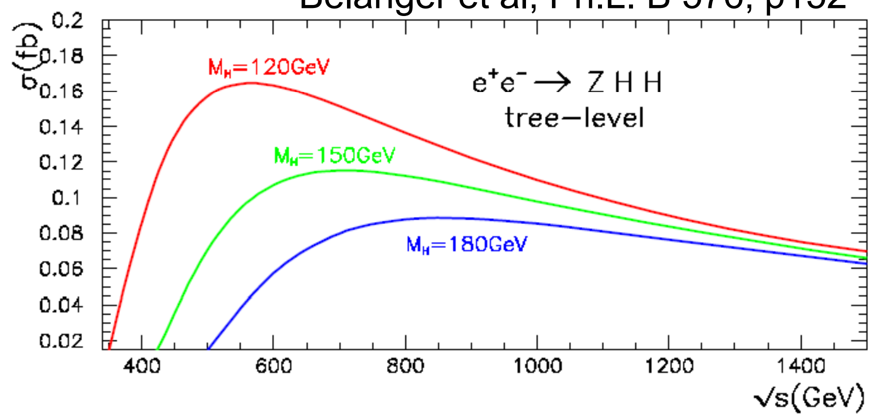
- If the SM is correct, the Higgs self coupling will be the last parameter to be tested:
  - Knowing the mass and all coupling of the Higgs it will be possible to have a strong theoretical prediction



irreducible backgrounds

- This process is best studied at 500 GeV and with a Higgs mass of 120 GeV
- Given the Z and Higgs SM decays:
  - BR (Z→qq) 70%
  - BR (H→bb) 73%
- Main channel is qqbbbb (40%)
  - ννbbbb (16%)
  - qqbbWW (12%)
  - llbbbb (only 4.5%)

Belanger et al, Ph.L. B 576, p152



Studying the ZHH process

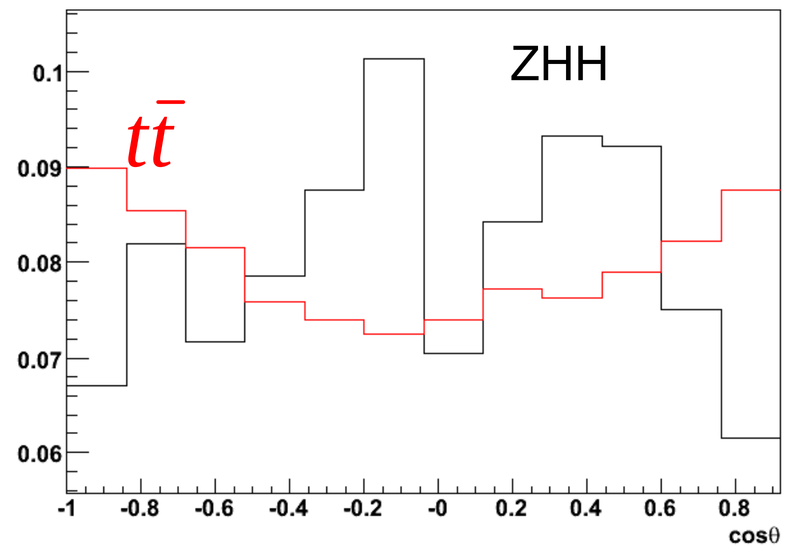
- ZHH is one of the main channels for ILD optimization:
  - It is a good benchmark of precision physics
  - Having a complex final state can be used to test software and detector performances
- The cross section is very small: 0.16 fb
  - 100 events in ILC first phase
- Main background: $t\bar{t}$ which has a cross section of 720 fb (4500 times the signal !!!)
- Use of polarized beams enhances the signal and suppress WW backgrounds
- First analysis using full simulation

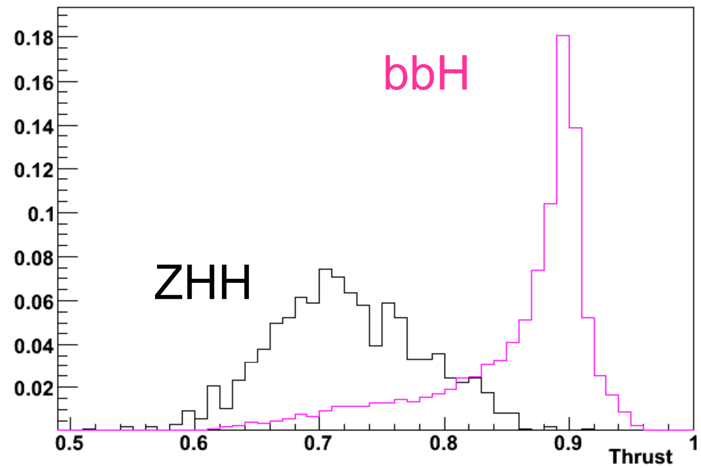
Analysis

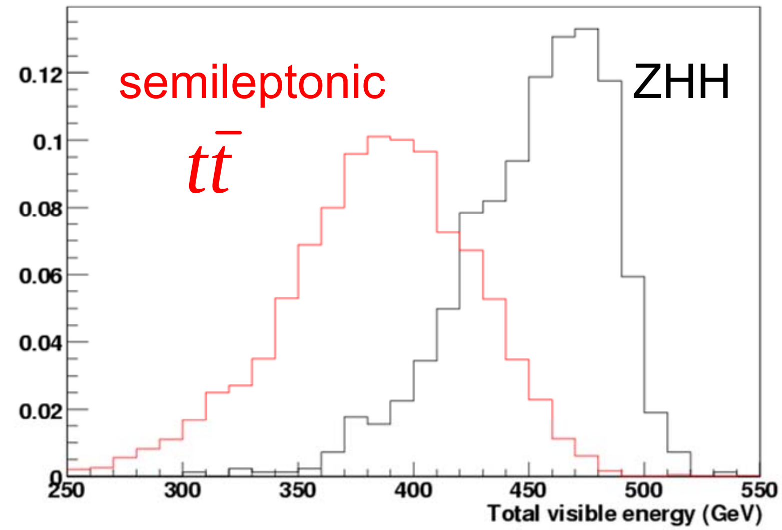
- Particle flow creates the clusters and performs particle ID
- 6 jets required in the analysis
- Jets are used by the vertex reconstruction to perform b tagging
- Preliminary cuts are applied
- Jets are combined to form the boson using a χ^2 variable
- The distribution of the minimized χ^2 is used to separate the signal and the backgrounds

Used cuts

- Topological cuts:
  - $\cos(\theta_{thrust})$
  - Thrust
  - Fox-Wolfram moments
- Missing energy:
  - |P(z)|
  - Total reconstructed energy





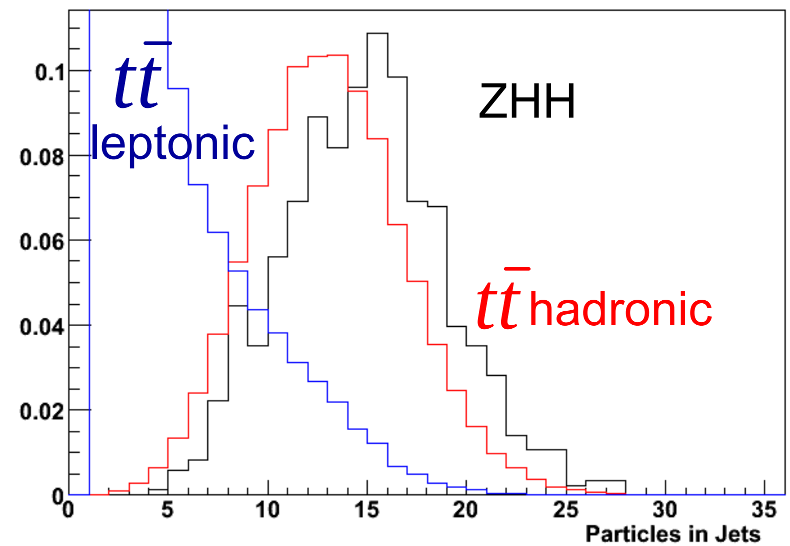


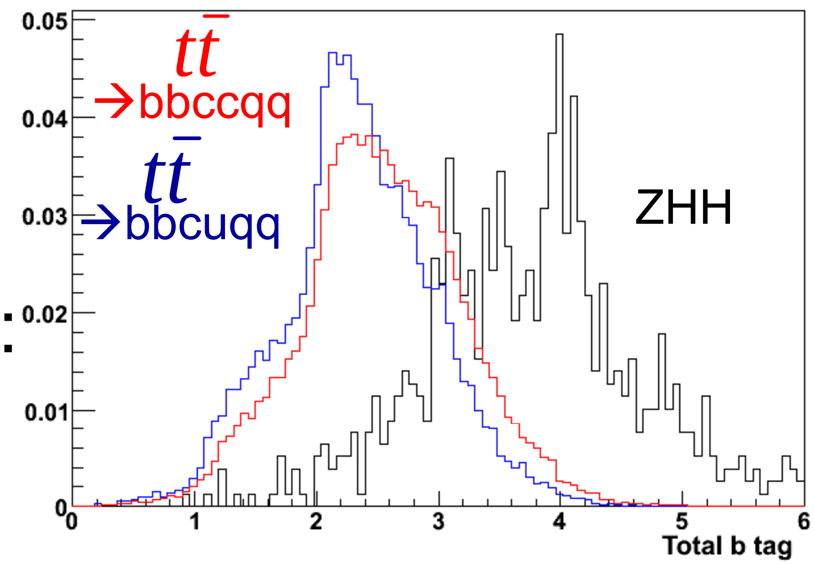
Used cuts

- 2 and 4 jets events can be rejected using:
  - Jets EnergyEM/Energy
  - Jet number of particles
  - Y_6
  - Number of charged tracks

- Multi variables optimization performed to maximize $S/\sqrt{(S+B)}$

- b tagging has a central role in reducing the background: requiring 4 b jets





Jet pairing

- The jets are combined in all 54 possible permutations
- For each permutation a χ^2 is evaluated
- The combination that give the minimum χ^2 is chosen
- Three possible scenarios have been studied:
  - Two using kinematic fitting
  - One without kinematic fitting

Kinematic fitting

mass terms

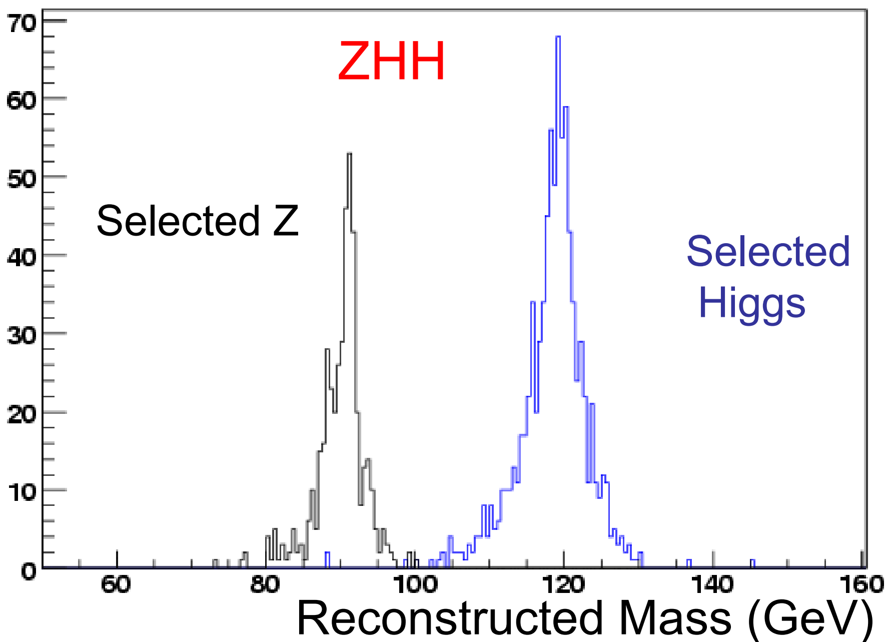
$$\chi^2 = \frac{\left(M_{12}^{fit} - M_Z\right)^2}{\Gamma_Z^2} + \frac{\left(M_{34}^{fit} - M_H\right)^2}{\Gamma_H^2} + \frac{\left(M_{56}^{fit} - M_H\right)^2}{\Gamma_H^2} +$$

$$\sum_{i=3,4,5,6} \frac{\left(NNbtag(i) - 1\right)^2}{\sigma_{btag}^2} + \sum_{i=1}^{6} \frac{\left(E^{fit} - E^{reco}\right)^2}{\sigma_{ene}^2} + \frac{\left(\sum_{i=1}^{6} E_i^{fit} - 500\right)^2}{\sigma_{beam}^2}$$

b-tagging — Jet energy constraint — Total energy constraint

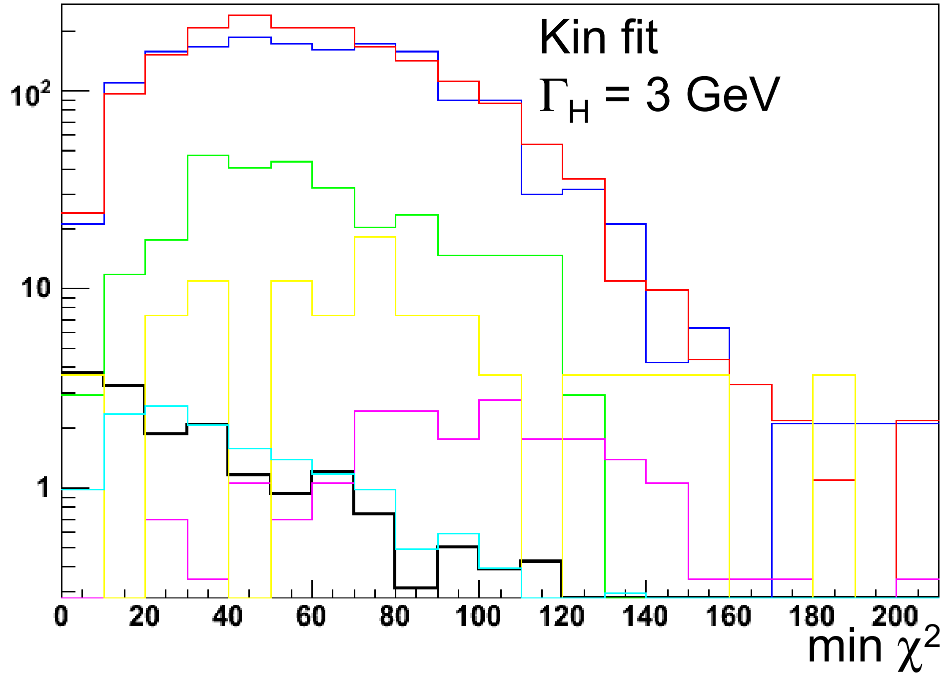
Γ_H can be:

- Hard constraint → 30 MeV
- Soft constraint Γ_H → 3 GeV



χ^2 distributions

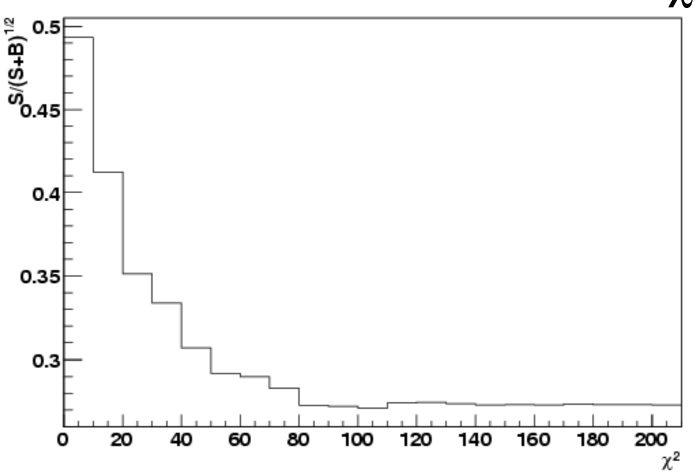
First look at 500 fb^{-1}



Partial background samples

- ZHH
- tt→hadronic → bbccqq
- tt→hadronic → bbcuqq
- tt→hadronic → bbuuqq
- tt→semileptonic
- ZZH
- bbH

$$\frac{S}{\sqrt{S+B}}$$



Best separation for χ^2 using kinematics fitting and soft constraint on the Higgs

Summary and Outlook

- Self coupling of the Higgs is the final test of the Standard Model and only ILC can perform this precision measurement
- The analysis is challenging, 6 jet final state
  - A set of cuts is performed using shape and topological variables
  - Three different χ^2 variables have been built using kinematics fitting
- The separation obtained correspond to an estimate on the resolution of the Higgs self coupling of 250%
- First analysis to use full simulation
- The use of a neural network to improve the analysis is under development

Backup Slides

Cross sections

Event type	σ (fb)	Events/500fb^{-1}	Generated events (PP)	Simulated events (Mokka)	% of available events/500fb^{-1}
Zhh (tot)	0.16	80			
Zhh→qqbbbb	0.0593	34	1000	1000	3375
ttbar (lept)	73	36500	100000	30000	82
ttbat (mixed)	310	155000	100000	45000	29
ttbar (cqcq)	82	41000	200000	41000	100
ttbar (uquq)	82	41000	200000	15000	37
ttbar (cquq)	164	82000	300000	41000	50
bbh	10.6	5300	30000	16000	302
ZZh	0.174	87	1000	1000	1150
ZZZ	1.05	525	0	0	0
WWZ	35.3	17650	0	0	0
tth	0.15	75	0	0	0
ttZ	0.7	350	0	0	0
tbW	16.8	8400	0	0	0

Effect of beam polarization

- Used realistic beam polarization
  - 80% for electrons
  - 0% for positrons

- The polarization has two effects:
  - Reduce WW fusion
    - WW → WW → Wtb is suppressed
  - Enhance Z channel → ZHH
    - But also tt production

$$\frac{S}{\sqrt{S+B}} = 0.49$$

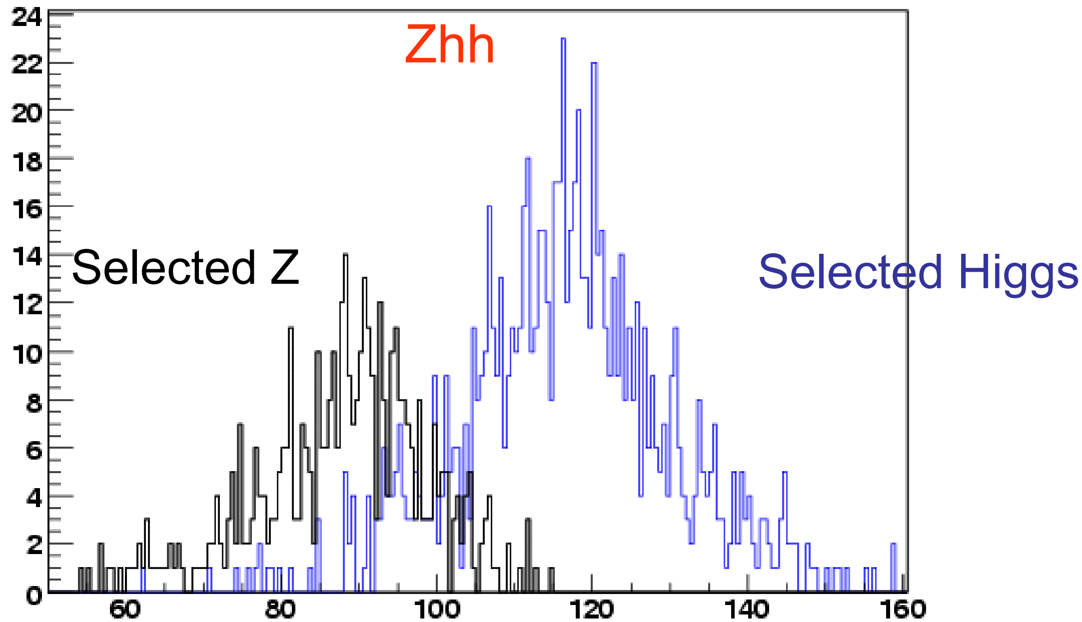
Simple selection

mass terms

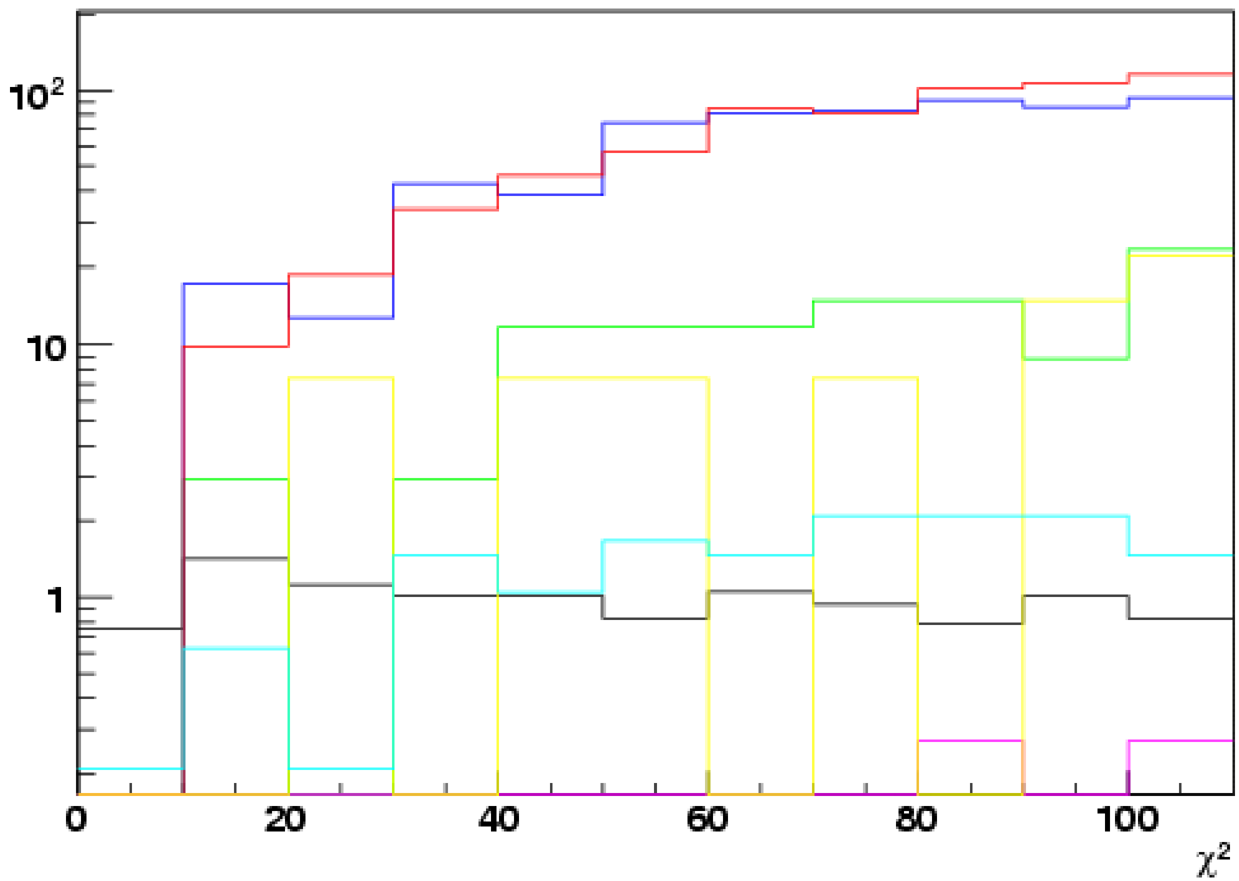
b-tagging

$$\chi^2 = \frac{\left(M_{12}^{fit} - M_Z\right)^2}{\Gamma_Z^2} + \frac{\left(M_{34}^{fit} - M_H\right)^2}{\Gamma_H^2} + \frac{\left(M_{56}^{fit} - M_H\right)^2}{\Gamma_H^2} + \sum_{i=3,4,5,6} \frac{\left(NNbtag(i) - 1\right)^2}{\sigma_{btag}^2}$$

For each event the combination of jets that minimize the χ^2 is chosen as the best combination to reconstruct the three bosons



Min χ^2 no kin fit



Zhh
tt→bbcqcq
tt→bbcquq
tt→bbuquq
tt→bbqqlν
ZZh
bbH

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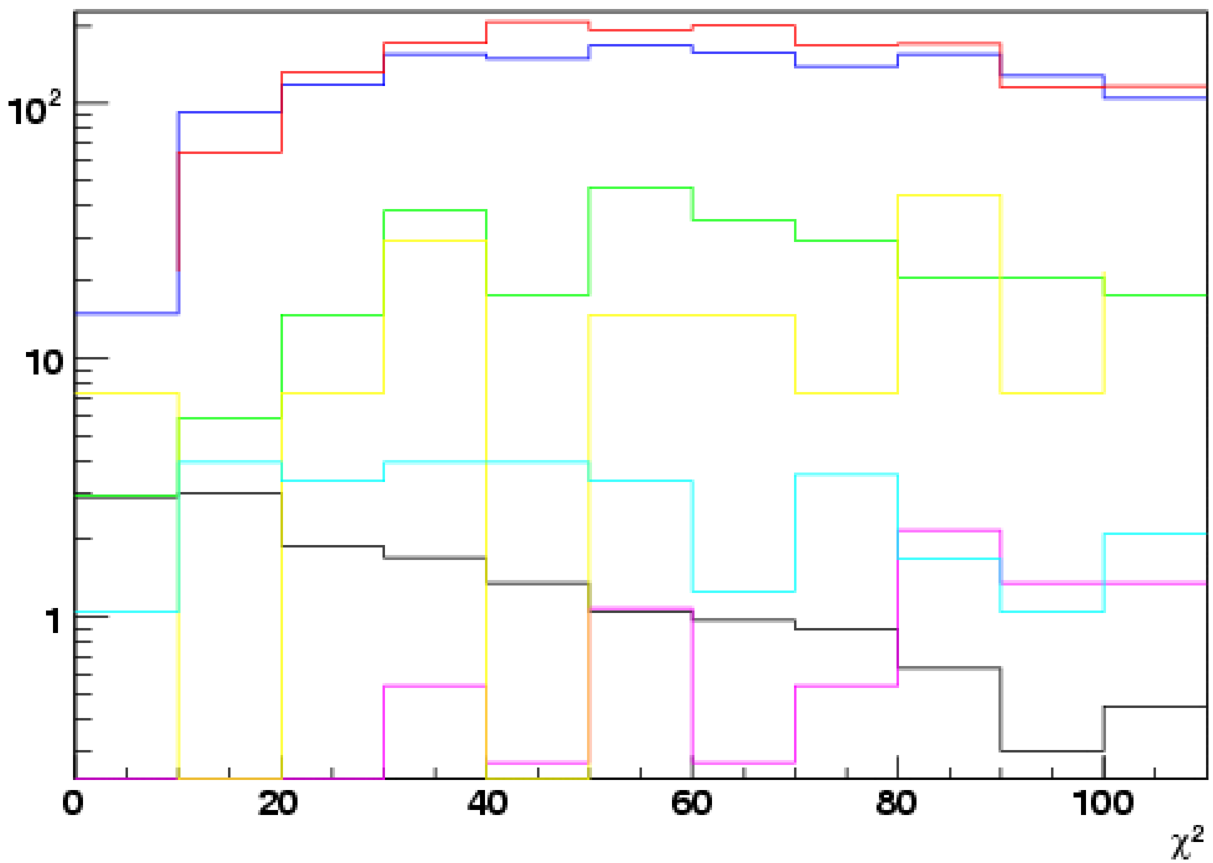
Min χ^2 kin fit natural Higgs



Zhh

tt→bbcqcq

tt→bbcquq

tt→bbuquq

tt→bbqqlν

ZZh

bbH

Signal/background separation

- Plots of $\frac{S}{\sqrt{S+B}}$

Best separation for χ^2 using kinematics fitting and sigma for Higgs comparable to Z resolution

Less than one event of signal