Model independent analysis for $HZ(Z \to q\bar{q})$ @ILC-250 and @FCC-250

Third JCL (Journés Collisionneur Linéaire)

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Motivation

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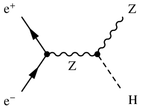
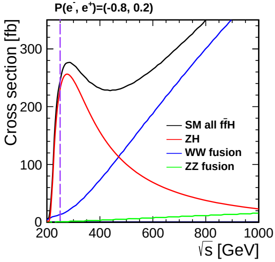
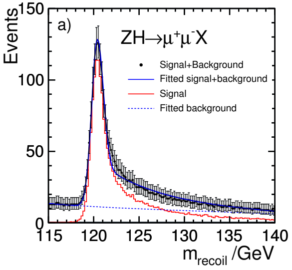
- ZH is the dominant Higgs production process @ 250 GeV e^+e^- machine
- $e^+e^- \rightarrow Z^* \rightarrow ZH$



- $M_H^2 = M_{recoil}^2 = (\sqrt{s} - E_Z)^2 - P_Z^2$
  - Model in dependent extraction of $g_{ZZH} \propto \sigma = N/(L \cdot \epsilon)$
- Reconstruct the M_{recoil} from the Z decay product only, without measuring the Higgs products
- Can we exploit $Z \rightarrow jj$ decays?
  - Increase the Higgs statistics $BR(Z \rightarrow q\bar{q}) \sim\rightarrow 70\%$ ($\sim 6\%$ for $Z \rightarrow \mu\mu$)
- Very difficult @ 250 GeV (ZZ/WW background)
  - $\rightarrow$ different Higgs efficiencies for different Higgs decay
  - Almost model independent
  - Could be better at higher $\sqrt{s}$

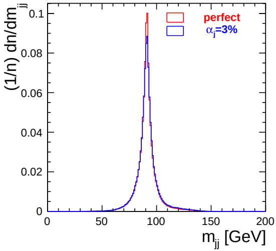


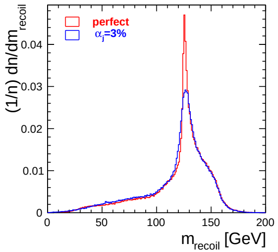


Analysis

Analysis Strategy

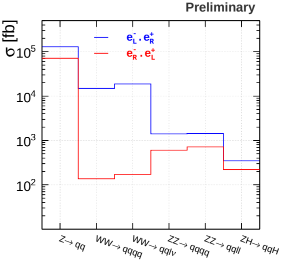
- Jet clustering of the stable + visible particles (no smearing of the particle energy at this stage)
- Jet reconstruction using Durham clustering algorithm
- Smearing of the reconstructed jet's energy
  - Energy : $\sigma(E_j)/E_j = \alpha$
  - Momentum :
    $\sigma(p_j) = \left(\frac{E_j}{P_j}\right)\sigma(E_j) = \left(\frac{E_j^2}{P_j}\right)\alpha$
- A $\alpha = 3\%$ is chosen
- Selection of the jet pair compatible with Z boson → the jet pair minimizing $D = |m_{jj} - m_Z|$
- Selection exploiting (almost) only the kinematics of the Z decay product
- Analysis of the di-jet recoil mass spectrum
- Only visible decays of Higgs are considered





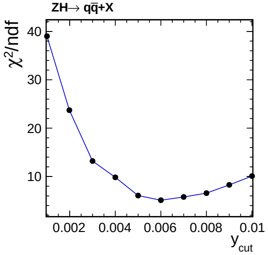
MC Samples

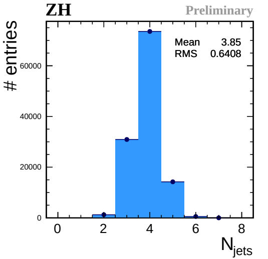
- Main backgrounds for 250 *GeV* Higgsstrahlung: W^+W^-, ZZ, $Z \rightarrow q\bar{q}$
- MC event samples generated with:
  - `WHIZARD-v1.95` Generator + `pythia-v6` for hadronisation
  - ISR + Beamstrahlung included
- Apply event weight for each process:
  - $w_i = L \cdot \sigma_i / N_i$
- Account for beam polarisation:
  - $w_i(e^-_R e^+_L) = (\frac{1+P(e^-)}{2})(\frac{1+P(e^+)}{2})$



Jet Clustering

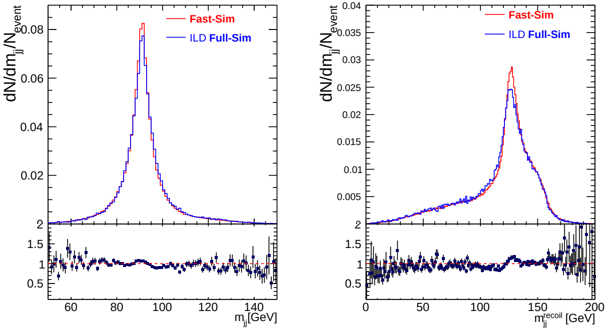
- No knowledge on the Higgs boson decay mode is employed in this analysis
- Various topologies:
  - 2 jet: $ZH \to q\bar{q} + inv \Rightarrow$
  - 4 jet: $ZH \to q\bar{q} + b\bar{b}$
  - 4-6 jet: $ZH \to q\bar{q} + WW/ZZ$
- Events cannot be forced into predefined number of jets
  $\Rightarrow$ Higgs selection must be unbiased
- Event resolved in arbitrary number of exclusive jets using:
  - **Durham algorithm with one parameter: y_{cut}**
- The selected di-jet mass is fitted by a Voigtian p.d.f (Breit-Wigner$\otimes$Gauss)
  - The $\chi 2$ vs $y_{cut} \to$ min at $y_{cut} = 0.006$
- The $y_{cut} = 0.006$ is chosen for the further analysis





Full Simulation vs Fast Simulation

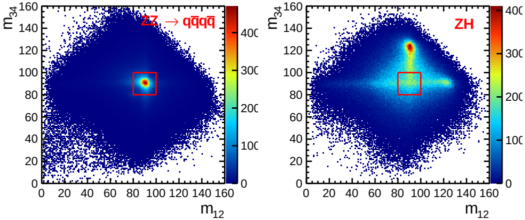
- Full simulation of ILD detector using the following configuration:
  - ECAL → Si-W ECAL option
  - HCAL → SDHCAL option
- The reconstruction of the Particle-Flow-Object is done by PandoraPFA



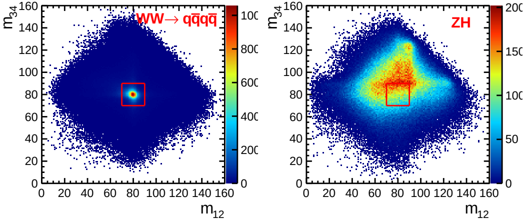
Background rejection

Preselection: $ZZ/WW \to q\bar{q}q\bar{q}$ vetoes

- Consider that each event is $ZZ \to q\bar{q}q\bar{q}$ ($WW \to q\bar{q}q\bar{q}$) $\Rightarrow$ force jet-clustering into 4 jets
- for the ZZ veto $\to$ choose jet pairing minimizing $\chi^2 = (m_{ij} - m_Z)^2 + (m_{kj} - m_Z)^2$



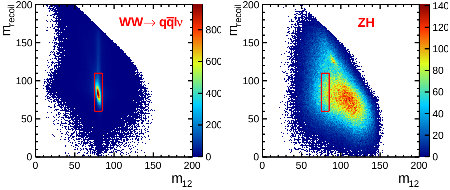
- for the WW veto $\to$ choose jet pairing minimizing $\chi^2 = (m_{ij} - m_W)^2 + (m_{kj} - m_W)^2$



- Cut on the selected pair masses (not on the recoil mass)

Preselection: $WW \to q\bar{q}l\nu$ veto

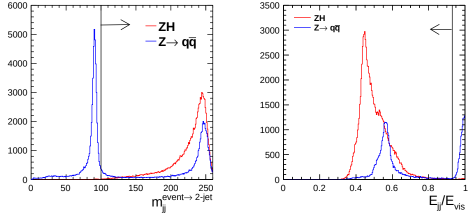
- Consider that each event is $WW \to q\bar{q}l\nu$ $\Rightarrow$ force jet-clustering into 3 jets
- Choose jet pair closest to the W mass



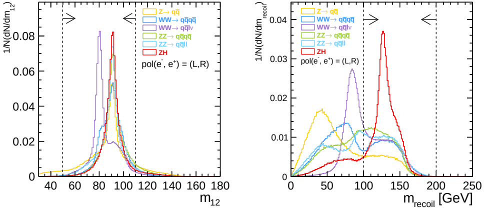
- Cut on the selected pair mass the corresponding recoil mass

Preselection: $Z \to q\bar{q}$ veto

- Consider that each event is $Z \to q\bar{q} \Rightarrow$ force jet-clustering into 2 jets

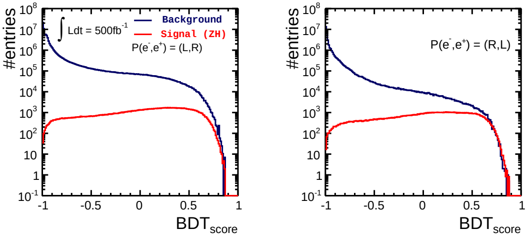


- Additional selection



MVA based selection

- Further selection → Boosted Decision Tree (BDT)
- The input variables are:
  - m_{jj} : invariant mass of the di-jet system
  - $|\cos\theta_Z|$: di-jet production angle
  - $\Delta\theta_{12}$: opening angle of the di-jet
  - $\Delta\phi_{12}$: opening angle of the di-jet is the transverse plan
  - $|\Delta E_{12}|$: largest boost from Z-pair → largest jet energy spread
  - $-\log_{10}(y_{23,34})$: `Durham` resolution parameters
- Train the BDT for combined backgrounds
- One BDT of each polarisation ($e^-_R e^+_L$ or $e^-_L e^+_R$)



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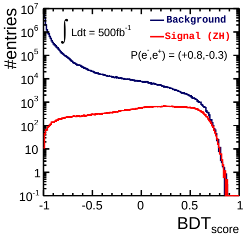
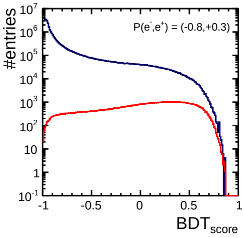
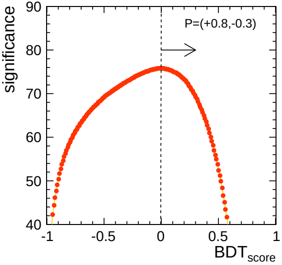
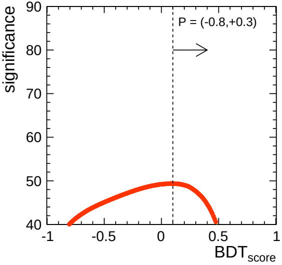




MVA Results

- Choose the cut value which maximises the significance
  - $\mathcal{S} = N_S/\sqrt{(N_S + N_B)}$
  - N_S = number of signal events, N_B = number of background events





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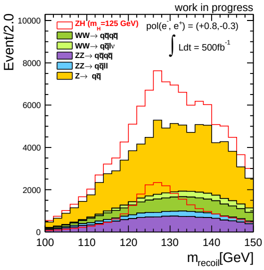
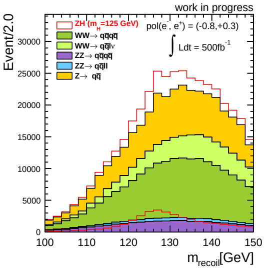
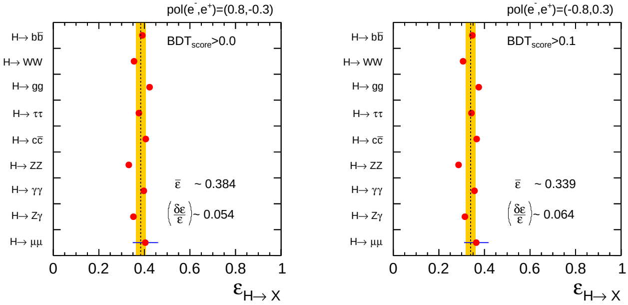




Testing the model independence

- The **model independence** of the Higgs tagging can be checked by estimating the efficiency in various decay modes
- The SM Higgs hypothesis is assumed here



- The analysis is sensible to the Higgs decay modes having a missing momentum
  - $H \to WW$, $H \to ZZ$ and $H \to Z\gamma$
  - Dependence might be corrected by a dedicated analyses ($H \to ZZ \to inv$)

Cross section estimation

- The cross section is estimated in both beam polarisation by
  - $\sigma_{ZH} = \sigma_{ZH}(Z \to q\bar{q})/BR(Z \to q\bar{q})$
  - with $\sigma_{ZH}(Z \to q\bar{q}) = (N - N_{bkp})/\varepsilon\mathcal{L}$

Beam polarisation	$\sigma_{ZH} = \sigma_{ZH}(Z \to q\bar{q})/BR(Z \to q\bar{q})$	σ_{ZH}^{SM}
$P(e^-, e^+) = (-0.8, +0.3)$	$301.11\text{fb} \pm (3.89)_{\text{stat}}$	300.66fb
$P(e^-, e^+) = (+0.8, -0.3)$	$202.98\text{fb} \pm (2.00)_{\text{stat}}$	203.05fb

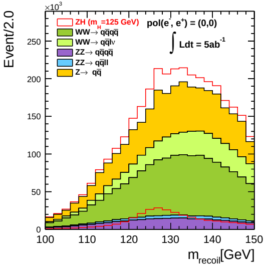
- The statistical error on σ_{ZH} can be estimated by $\sqrt{N}/(N - N_{bkp})$
- The σ_{ZH} is proportional to g^2_{HZZ} (coupling at HZZ vertex)

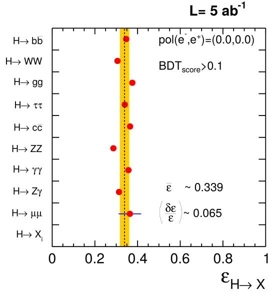
Beam polarisation	$\left(\frac{\delta\sigma_{ZH}}{\sigma_{ZH}}\right)_{\text{stat}}$	$\left(\frac{\delta g_{HZZ}}{g_{HZZ}}\right)_{\text{stat}}$
$P(e^-, e^+) = (-0.8, +0.3)$	1.85%	0.92%
$P(e^-, e^+) = (+0.8, -0.3)$	1.41%	0.70%

- **A statistical precision $\sim 1\%$ can be reached on g_{HZZ}**

In the circular colliders

- Example of CPEC (China) or FCC-ee ($5\ \mathrm{ab}^{-1}$, $10\ \mathrm{ab}^{-1}$)
- Higher luminosity comparing to linear colliders
- Beamstrahlung effect is negligible $\rightarrow$ the results might be better





Beam polarisation	$\left(\frac{\delta\sigma_{ZH}}{\sigma_{ZH}}\right)_{\mathrm{stat}}$	$\left(\frac{\delta g_{HZZ}}{g_{HZZ}}\right)_{\mathrm{stat}}$
$P(e^-, e^+) = (0,0)$	0.65%	0.32%
$P(e^-, e^+) = (0,0)$	0.65%	0.32%

- **A statistical precision $\sim 0.3\%$ can be reached on g_{HZZ}**

Analysis conclusion & outlook

- Development of fast simulation using SDHCAL performance
- Demonstration of feasibility of almost model independent analysis at $\sqrt{s} = 250\mathrm{GeV} \rightarrow \sim 5\%$ bias level
- Precision on the σ_{ZH} of 1.4% have been reached

- Sensitivity/efficiency of the analysis as function of jet energy resolution
- Determination of an optimal $\sqrt{s}$ for a running ILC
    - Possible change on the ILC baseline under discussion

Backup

MC processes statistics

	$N_{jet} \geq 2$	σ $[fb]$	N_{events}	weight ($L = 500$ fb^{-1})
$e_L^- e_R^+$	$ZH(qq+X)$	346.013	437368	0.395563
	$WW(qqqq)$	14874.3	1074111	6.92401
	$WW(ql\nu)$	18781	1753663	5.35479
	$ZZ(qqqq)$	1402.06	1004632	0.697798
	$ZZ(qqll)$	1422.14	1299591	0.547149
	$Z(qq)$	129149	1629438	39.6299
$e_R^- e_L^+$	$ZH(qq+X)$	221.952	267357	0.415085
	$WW(qqqq)$	136.357	136325	0.500117
	$WW(qql\nu)$	172.733	158021	0.546551
	$ZZ(qqqq)$	604.971	603931	0.500861
	$ZZ(qqll)$	713.526	637256	0.559843
	$Z(qq)$	71272.8	1676503	21.2564