Sensitivity to the Higgs Self-coupling Using the ZHH Channel

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The Standard Model predicts the value of the Higgs self-coupling but it cannot be measured at LHC. This measurement requires a machine such as the proposed International Linear Collider. Here, the sensitivity to the Higgs self-coupling is evaluated using the ZHH to six jets channel for a Higgs mass of 120 GeV/c². Full simulation has been carried out for an integrated luminosity of 500 fb⁻¹. Several analyses are presented and all evaluate the cross section resolution to be about 180%. Potential areas for improvement are identified.

1 Introduction

At the energy of the International Linear Collider (ILC), the process e⁺e⁻ → ZHH is the only one that can be used to measure the self-coupling of the Higgs boson. This study was performed assuming M_H = 120 GeV and a centre-of-mass energy of 500 GeV at which the total cross section is 0.183 fb, assuming a polarisation of -80% for the electron beam. The main decay mode is the six-jet final state with a BR of about 40%, which is the only final state considered in this analysis. The integrated luminosity was assumed to be 500 fb⁻¹ which corresponds to the planned integrated luminosity for the first phase of ILC.

2 Generation, simulation and reconstruction

The events used in the ZHH analysis were generated using Pandora Pythia [2] and WHIZARD [3]. The two generators were compared and are compatible. Since it is computationally impossible to perform the simulation for the whole 500 fb⁻¹, only events with six quarks in the final state and a selection of four-jet final states were considered. Table 1 summarises the events generated. The main background is the hadronic t¯t channel which has a total cross section of 326 fb. For the ZZ channel it was required to have at least one Z decaying in heavy quarks (c, b).

The detector simulation was performed using MOKKA v00-06-04p02. The detector model used was LDC00Sc [4].

The simulated events were reconstructed using Marlin v00-09-10. The hits in the tracking and calorimetry systems were digitised and then used as input for the tracking (FullLDC package) and particle flow reconstruction (PandoraPFA package). The particles were forced to six jets using the Durham algorithm and the jets were analysed by the vertex reconstruction software (LCFI package) to reconstruct b and c vertices. The same reconstruction

| Channel | ZHH | tt | WWZ | ZZH | ZZZ | ZZ | ZH | tbtb | Wtb | ttH | ttZ |
|---------|-----|----|-----|-----|-----|----|----|------|-----|-----|----|
| σ(fb)   | 0.183 | 711 | 212.9 | 0.502 | 1.486 | 90.5 | 13.66 | 0.434 | 44.34 | 0.237 | 1.016 |
| Events  | 10k | 375k | 120k | 1000 | 5000 | 50k | 20k | 5000 | 25k | 5000 | 5000 |

Table 1: Signal and principal background channels and number of events generated for each.
chain was performed using the “perfect” particle flow reconstruction, in which all particles are correctly reconstructed, essentially neglecting any confusion term from the calorimeters. Details of all the software used can be found in [5]. The reconstructed particles and the jets, for both realistic and perfect PFA chain of reconstruction, were then used to calculate several shape variables which were used in this analysis.

3 Cut based analysis

A key variable used to separate signal from background was the sum of all outputs from the b tagging neural network. This is a number from 0 to 1 for each jet, where 1 indicates b-like jets and 0 light-like jets. Having 6 jets, the variable used in the analysis varies between 0 and 6 with the signal peaking at 4 and the main background at 2. The other variables used were: thrust, \( \cos \theta_{\text{thrust}} \), second Fox-Wolfram moment, total energy, number of tracks, number of particles in jet, angular distance between jets (Y6) and jet EM energy ratio. These variables were optimised by scanning simultaneously all variables over a wide range of values. However the high number of variables made it difficult to test many values because of the processing time and the memory requirement. A satisfactory compromise was found using five cut values for each variable and reiterating the process to find the exact maximum. For each iteration, among all possible combination of cuts (there are \( 5^8 \)), the one that maximised the usual figure of merit \( S/\sqrt{S+B} \) was chosen. After few iterations the value of \( S/\sqrt{S+B} \) did not improve any further and the process was ended. The final value for \( S/\sqrt{S+B} \) after applying all the cuts was 0.364±0.011. A similar optimisation was performed for the perfect PFA reconstruction obtaining \( S/\sqrt{S+B} = 0.361 \pm 0.010 \).

In order to further separate signal from background, a \( \chi^2 \) was built to force the reconstruction of each event to ZHH:

\[
\chi^2 = \left( \frac{(M_{ij} - M_Z)^2}{\sigma_Z^2} \right) + \left( \frac{(M_{kl} - M_H)^2}{\sigma_H^2} \right) + \left( \frac{(M_{mn} - M_H)^2}{\sigma_H^2} \right) + \frac{4}{\sum_{J_H=1}} A(Btag(J_H) - 1)^2.
\]

All forty five combinations of the six jets were tried. The combination that produced the smallest \( \chi^2 \) defined the \( \chi^2_{\text{min}} \) for that event. \( \chi^2_{\text{min}} \) was then used to discriminate signal from backgrounds. However the large number of \( t\bar{t} \) passing the previous cuts can be reconstructed to look similar to ZHH events due to the high combinatorial in jet pairing. For this reason a second \( \chi^2 \) was built adding the b tagging information:

\[
\chi^2 = \left( \frac{(M_{ij} - M_Z)^2}{\sigma_Z^2} \right) + \left( \frac{(M_{kl} - M_H)^2}{\sigma_H^2} \right) + \left( \frac{(M_{mn} - M_H)^2}{\sigma_H^2} \right) + \sum_{J_H=1}^4 A(Btag(J_H) - 1)^2.
\]

The new term uses the b tag information with the value of \( A \) which has been found to be very large after an optimisation. Since the four jets from the two Higgs bosons should be b jets, the output of the b tagging neural network should peak at 1 hence the sum of the four terms should peak at zero for well reconstructed and well associated jets in signal events. Since b-like jets are more likely to form one of the Higgs boson instead of the Z, the new term effectively reduces the number of possible combinations. This reduction in combinations has a small impact on the signal but reduces all the backgrounds.

The optimisation of the parameter \( A \) was performed varying the value from 0 to \( 10^5 \). For each value of \( A \) the same procedure described before was performed; the minimised \( \chi^2 \) was
plotted for signal and background and from this distribution the $S/\sqrt{S+B}$ was maximised. Figure 1 shows the maximum of $S/\sqrt{S+B}$ as a function of $A$. The error is the statistical error mainly due to the limited number $t\bar{t}$ events. For values above 100 the separation is constant at a value of $0.55 \pm 0.06$.

Kinematic fit of the six jets to further constrain the reconstruction was implemented but the separation was not improved. This and the fact that the optimisation of $A$ is asymptotic and does not have a peak, are indications that the mass resolution is less important than the b tagging performance. A separate analysis on the events with perfect PFA reconstruction confirmed this indication. In fact the separation for the perfect reconstruction is $S/\sqrt{S+B} = 0.59 \pm 0.06$, which, within the statistical error, is compatible with the case of realistic PFA. This means that any improvement in the PFA will not reflect in a better separation in this analysis. In order to have a better separation the other main element of the selection, the vertex reconstruction for the b tagging, has to be improved.

Figure 1: $S/\sqrt{S+B}$ as a function of $A$.

4 Neural network analysis

A second analysis was performed using a neural network, which in principle should give a better separation between the signal and the backgrounds then the cut based one. The network implementation was performed using the artificial neural network (ANN) package within TMVA [6]. A separate sample of signal and background events was generated to train the neural network. For the background, an integrated luminosity of 125 fb$^{-1}$ was generated while for the signal 30000 events were used. The preliminary cuts described above were applied to the training sample and the events passing the cuts were used to train the network. Due to the limited number of events left, only a simple network could be trained; in particular two configurations were studied. The variables used were the b tagging, the $\chi^2_{ZHH}$ and the $\chi^2_{t\bar{t}}$. The two $\chi^2$ variables are defined in Eq. 1 but the b jets were forced to came from the Higgs or from the decay of the top.

The $S/\sqrt{S+B}$ were obtained as before, looking for the maximum as a function of the neural network output; the results are summarised in Table 2. Within the statistical error, neither of the two networks improved the separation between signal and background. This is a further confirmation that, at the moment, the mass information does not have any discriminating power.

5 Conclusion

Given the relevance of the b tagging performance in the analysis, a dedicated study was performed to study the performance in the six-jet environment. The efficiency in b tagging for b, c and light jets was compared between the two-jet and the six-jet environment. The
comparison showed an increase of about 25% in the fake rate from c jets while the light jets in the six-jet environment had a fake rate doubled with respect to the two-jet environment. This increase is due to the different environment but also to the different energy of the jets. A separate study of two-jet events of different energy showed that the fake rate increases at higher energies with respect to the nominal value obtained with jets from the decay of a Z boson at rest.

| Analysis                        | $S/\sqrt{S+B}$ | S   | B   |
|---------------------------------|----------------|-----|-----|
| Simple $\chi^2$                 | 0.36 ± 0.01    | 13.5| 1364.5|
| $\chi^2$ with b tag term       | 0.55 ± 0.06    | 4.0 | 47.0 |
| $\chi^2$ with b tag term and kin. fit. | 0.56 ± 0.06    | 6.4 | 124.4 |
| NN two variables                | 0.57 ± 0.06    | 5.8 | 99.2 |
| NN three variables              | 0.55 ± 0.06    | 7.5 | 186.0 |

Table 2: Best $S/\sqrt{S+B}$ for different NN and cut based analyses.

If a similar performance could be achieved in the six-jet environment as in the two-jet events, the resolution would improve by a factor two. Then, without performing any further optimisation, the resolution on the ZHH cross section would be about 95%. This value is not too distant from those obtained in fast Monte Carlo studies, about 80% for [7] and 60% for [8], if the same integrated luminosity is considered and if effects such as the gluon emission are considered. The remaining difference is likely to be due to detector effects, such as confusion in particle reconstruction. It is important to stress the fact that this is an indirect comparison; in order to have an accurate estimate of the differences between fast and full simulation, the same events should be compared using the same analysis. Further improvement could be achieved considering also the decay of the Z to neutrinos.

References

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