Higgs Self-Coupling at centre-of-mass energy of 500 GeV

P. Gay

Laboratoire de Physique Corpusculaire, Univ. B. Pascal/IN^2P^3-CNRS, 24 Av. des Landais, F-63177 Aubière Cedex, France

Abstract. The measurement of the trilinear self-coupling of the Higgs boson would experimentally determine the structure of the Higgs potential. Feasibility of such a measurement has been investigated with the analysis of both full hadronic and semi-leptonic final states of the double-Higgs strahlung process in e^+e^- collisions at centre-of-mass energies delivered by the future Linear Collider.

Introduction

The reconstruction of the Higgs potential is an essential step in the experimental validation of the Higgs mechanism that lies at the core of the standard model. In that context, the measurement of the trilinear self-coupling (λ_{hhh}) offers an independent determination of the Higgs potential shape. The aim of the study is to demonstrate how to measure the trilinear self-coupling λ_{hhh} in e^+e^- collisions at center-of-mass energies delivered by the future Linear Collider. At low energies, namely around 500 GeV, the trilinear Higgs self-coupling could be extracted from the measurement of the cross-section of the double Higgs-strahlung ($e^+e^- \to \mathrm{Zhh}$) [1,2]. The major Feynman diagrams involved in this process are reported in Fig. 1.

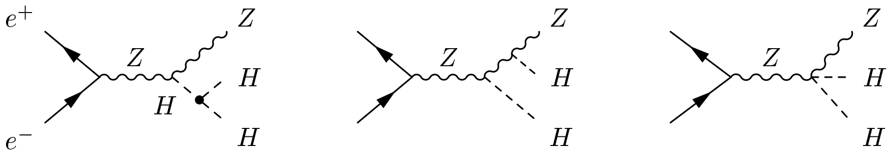

FIGURE 1. Feynman diagrams involved in the $e^+e^- \to$hhZ cross-section via the double Higgs-strahlung.

For light Higgs boson masses, the Higgs boson decays predominantly in a $\mathrm{b\bar{b}}$ pair. When the Z decays in a lepton pair, the final state is $\mathrm{hhZ \to b\bar{b}b\bar{b}}\ell^+\ell^-$. With a high b content and two leptons, this topology produces an easy signature but represents only $\sim$ 8% of the total final state. By contrast, the hhZ$\rightarrow$b$\bar{\text{b}}$b$\bar{\text{b}}$q$\bar{\text{q}}$ final state benefits from a high statistics with $\sim$ 60% of the final states but requires a more complicated analysis. If the mass of the Higgs boson is assumed to be light ($\sim$120GeV/c^2) then the best centre-of-mass energy is around 500 GeV [1]. The study presented here will be performed for m_{h}=120 GeV/c^2 and $\sqrt{\text{s}}$=500 GeV and it is restricted to the standard model framework. Nevertheless, in such conditions, the signal cross-section is still very tiny with a 0.18 fb value and for an expected integrated luminosity of 500 fb^{-1}, only 93 signal events are produced.

Analysis

The background sources are either two fermions final state processes as e$^+$e$^-$$\rightarrow$Z$\gamma$, or four fermions as e$^+e^-$$\rightarrow$W$^+W^-$, ZZ, We$\nu$, Zee, hZ, t$\bar{\text{t}}$ and six fermions final state like e$^+$e$^-$$\rightarrow$WWZ or ZZZ. Since e$^+e^-$$\rightarrow$t$\bar{\text{t}}$ and e$^+$e$^-$$\rightarrow$Wtb will yield major contributions to the background, an emphasis has been performed and a simulated luminosity greater than 2000 fb^{-1} was generated for such processes as well as for six fermions processes. Details about generators and event samples used are reported in Ref. [3]. The detector simulation was performed with a Parametric Monte Carlo [4] including a tracking system, immersed in a 3 tesla magnetic field, electromagnetic and hadronic calorimeters and luminometer at low angle to enforce the hermeticity of the detector. According the studies performed with full simulation of high granularity calorimeters [5], a jet energy resolution of 40%/$\sqrt{E_{jet}}$ has been assumed. The b-tagging is performed through a parametrisation derived from full reconstruction [6].

Both final state, hhq$\bar{\text{q}}$ and hh$\ell^+\ell^-$ are characterized by six jets (an isolated lepton is considered as a jet), and the hadronic system is characterized by a high b content. After a preselection mainly based on event shape variables, the the b-content as well as the di-jets reconstructed masses are used. In a last stage, all the relevant informations are combined with a multivariable method. The analysis features are detailed in Ref. [3]. The number of events expected from background processes at the preselection level are reported in Table 1. Around 48.10^3 background events are expected with a luminosity of 500 fb^{-1} while $\sim$42 and $\sim$7 signal events are expected for hhq$\bar{\text{q}}$ and hh$\ell^+\ell^-$ final state respectively when m_{h}=120 GeV/c^2 is assumed. Major sources of background are processes with at least one top quark in the final state. However, even if the background contribution is largely reduced, the remaining part is three order of magnitude greater than the signal. Thanks to the jet energy flow resolution, a direct use of the reconstructed di-jets masses is applied. Among all the di-jets masses in the event, the so-called m_{56} mass minimizes the difference with a m_{Z} hypothesis. The b content of the system recoiling to the Z ($\mathcal{B}^{\text{recoil}}$) is an excellent variable to reject contribution from background processes and at least two b jet among the recoiling jets system ($\mathcal{B}^{\text{recoil}}$>2) is requested. Among the four jets recoiling to the Z (*i.e.* m_{56}), the di-jets masses m_{12} and m_{34} are defined by minimizing $\|m_{12}$-$m_{34}\|$ and both m_{12} and m_{34} have to be larger than

100 GeV/c^2.

The contribution from the various background sources are reported in Table 1. The signal efficiencies is 35% and most of the background is coming from $e^+e^-\to$Wtb and $e^+e^-\to t\bar{t}$ processes while the six fermions final state contribution is due to $e^+e^-\to$ZZZ with relatively small level with respect to the previous contributions. In order to take into account the correlation between the di-jets masses and the b content of the event, the variables m_{12}, m_{34}, m_{56} and $\mathcal{B}^{\rm recoil}$ are combined with a neural network (NNet). Restricted to the positive values, Fig. 2 displays the NNet output from signal and background processes while the contributions from the background sources are indicated in Table 1. The signal efficiency is about 36%. With an integrated luminosity of 500 fb^{-1}, a cut on the NNet output at 0.5 leads to 31 signal events while 27 background events are expected corresponding to a s/$\sqrt{\rm b}$ of $\sim$ 6. This discrimination is fully used in the cross-section measurement where a fit of the NNet output distribution is performed.

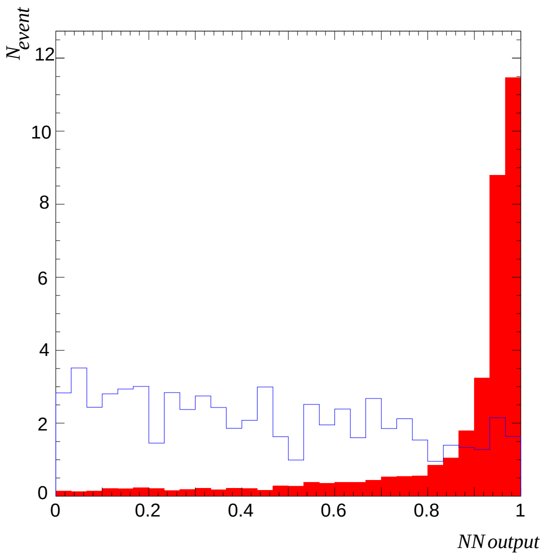

FIGURE 2. Neural Network output distribution (NN_{output}) for HHZ signal (full histogram) and background (empty histogram) with 500 fb^{-1} and $m_{\rm h}$=120 GeV/c^2.

TABLE 1. Numbers of events with $\mathcal{L}$= 500fb^{-1} expected both for signal (hhZ) and background (bkg.) processes at preselection level (presel.), standard selection (selec.) and multivariable analysis (NNet).

	hhq$\bar{\rm q}$	hh$\ell^+\ell^-$	hhZ	WW	Zγ	ZZ	WWZ	ZZZ	hZ	t$\bar{\rm t}$h	bkg.
presel.	41.4	6.7	49.1	2114.	44938.	484.	331.	56.6	174.	3.	48089.
selec.	27.1	5.1	32.2	74.3	34.	0.	0.	9.	0.	0.	117.4
NNet	27.5	6.4	33.9	32.	24.	0.	0.14	8.4	0.	0.	64.3

Results

The cross-section of the $e^+e^- \to hhZ$ process have to be measured, in order to extract λ_{hhh}. Such a measurement is performed by a likelihood fit of the NNet output. The relative error obtained on the cross-section measurement are 20.4%, 12.9% and 10.3% for integrated luminosity of 0.5, 1 and 2 ab^{-1} respectively. Relative errors on the $e^+e^- \to hhZ$ cross-section has been evaluated for higher Higgs boson masses up to 140 GeV/c^2 [3]. The relation between λ_{hhh} and the cross-section has to be taken into account to derive the relative error $(\Delta\lambda/\lambda)$ on λ_{hhh}. As indicated by the Fig. 1, only one diagram for the $e^+e^- \to hhZ$ cross-section is sensitive to λ_{hhh}. The other ones constitute an irreducible background for the λ_{hhh} measurement which makes the measurement intrinsically difficult. With an integrated luminosity of 2 ab^{-1}, the relative precision $\Delta\lambda/\lambda$ is 18%, and relaxes to 22% with half of that luminosity.

Conclusions

To establish the Higgs mechanism in an unambiguous way, the self-energy potential of the Higgs field must be reconstructed. The experimental feasibility of the λ_{hhh} measurement has been explored trough a detailed analysis of the reconstruction of the double Higgs-strahlung events taking advantage of the characteristic signature with four b jets and a Z boson, reconstructed either in its leptonic or hadronic decay modes. The tiny signal cross-section and the large four and six fermion background processes make of this measurement a genuine experimental challenge. An excellent tagging as well as reconstruction capabilities of high granularity calorimeters are then essential. Using a Neural Network method and with help of high integrated luminosity (2 ab^{-1}), the determination of the $e^+e^- \to hhZ$ cross-section with a 10% relative error could be achieved leading to a relative error on λ_{hhh} of 18%.

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