On the determination of the structure of the scalar Higgs boson’s couplings to vectorbosons

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Abstract

In this paper we investigate the determination of the coupling structure of a Higgs boson at the LHC using angular correlations in the decay chain $H \rightarrow ZZ \rightarrow l_1^+l_1^-l_2^+l_2^-$. We consider the most general couplings of a scalar to spin 1 particles and compare the angular correlations of the decay products using a maximum likelihood method. We use the full information from the LO matrix element including all possible correlations between the decay angles. In our analysis we include all possible mixings between the different coupling structures. We conclude that the coupling structure can in general be determined using this approach. But it has to be noted, that for Higgs boson masses below the ZZ-threshold the analysis is statistically limited. For higher Higgs boson masses reasonably strong limits on non standard couplings can be achieved at the LHC using the full integrated luminosity of $300 \text{ fb}^{-1}$.

Key words: LHC, Higgs
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1 Introduction

In a recently published article [1], see also [2], we have demonstrated that the angular correlations of the decay leptons of Z pairs originating from Higgs boson decays can be used to distinguish the spin/CP state $0^+$ of a Higgs boson from hypothetical states with quantum numbers $0^-, 1^+$ and $1^-$. Only pure CP eigenstates were considered in that article. In this letter we show that the analysis can be generalized in order to achieve a more complete determination of the coupling structure of the scalar standard model Higgs boson. We are using the full lagrangian from [1] for the coupling of a spin 0 particle to two vector bosons:

$$\mathcal{L} = X \delta^{\mu\nu} + Y \frac{k^{\mu}k^{\nu}}{M_h^2} + P \epsilon^{\mu\nu\rho\sigma} p_1^{\rho}p_2^{\sigma},$$

(1)

where $k$ is the momentum of the Higgs boson and $p_1, p_2$ are the momenta of the Z bosons. One or more of the parameters $X$, $Y$ or $P$ can be non-zero which allows for mixed states. We demonstrate that the values of $Y/X$ and $P/X$ can be measured simultaneously. We determine to what precision their consistency with zero can be established using the Atlas-Experiment.

2 Signal selection

In order to gain realistic results the signal selection process has to be taken into account carefully. We use the performance of the Atlas-detector, but in general the method is not limited to this particular experiment. The event generation and reconstruction simulation has been carried out using Atlfast within the Athena framework[3]. We use the selection criteria as set forth in the Atlas-TDR. Two isolated leptons are required within a pseudorapidity region of $|\eta| < 2.5$ with a transverse momentum of more than 15 GeV. This reliably triggers the experiment. Two additional leptons in the same pseudorapidity region with a transverse momentum of more than 7 GeV are required. The leptons have to have appropriate flavour and charge to be combined to two Z bosons.

For Higgs masses below the threshold for the production of two on-shell Z the reducible non-resonant background from $Zb\bar{b}$ and $t\bar{t}$ production becomes increasingly important. In order to cope with this background, further cuts on the masses of the Z candidates and the impact parameter are imposed. A

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Table 1

| Higgs mass [GeV] | 120 | 130 | 140 | 150 | 160 | 170 | 180 |
|------------------|-----|-----|-----|-----|-----|-----|-----|
| Window $m_{12}$ [GeV] | 20  | 15  | 15  | 10  | 10  | 6   | 6   |
| Threshold $m_{34}$ [GeV] | 15  | 20  | 25  | 30  | 45  | 45  | 60  |

Mass window $m_{12}$, for the invariant mass of one lepton pair, and threshold $m_{34}$ for the second pair. (See [5])

detailed study of the effect of these cuts can be found in [5]. The invariant mass of one of the lepton pairs has to lie within a mass window $m_{12}$ around the Z mass, while the mass $m_{34}$ of the other pair has to be greater than a certain threshold. The value of the window and the threshold are optimized for different Higgs masses (see table 1). The effect of an impact parameter cut on the purity of the sample has been studied in detail in [5]. By applying such a cut the reducible backgrounds can be suppressed about ten times below the irreducible ones. Thus the contribution of these backgrounds is expected to be negligible. The overall lepton efficiency was assumed to be 90% per lepton, which is rather conservative. No K-factors have been taken into account. The number of events for signal and background we found are similar to those published in the TDR. It is worth noting that the absolute number of background events is - within a certain range - not crucial for the analysis. A proper normalization of the background with data using the sidebands is far more important.

Lacking an underlying physical theory predicting the non standard model like couplings, $\mathbf{Y}$ and $\mathbf{P}$, we have to give a physical interpretation for the strength of the couplings. A normalization of the couplings is necessary in order to have a criterium to determine whether the non-standard couplings are large or small and thereby whether the experiment is precise or imprecise. The arbitrariness of the mass used to normalize the mass dimension of the coupling constants underlines this need. As a simple criterium we compare the width of the states with only $\mathbf{P}$, $\mathbf{Y}$ or $\mathbf{X}$ couplings and require that the full width of these states is the same for all three couplings. This yields factors to be applied to the parameters $\mathbf{P}$ and $\mathbf{Y}$

$$R_P = \sqrt{\frac{\Gamma_{SM}}{\Gamma_P}} , \quad R_Y = \sqrt{\frac{\Gamma_{SM}}{\Gamma_Y}}$$

(2)

These factors are listed in table 2 for various values of the Higgs mass. By applying these factors we redefine the coupling parameters so that now the coupling strength is equal for all couplings.

$$\mathbf{P}' = R_P \cdot \mathbf{P} , \quad \mathbf{Y}' = R_Y \cdot \mathbf{Y}$$

(3)

It is to be noted, that this is not the only way to parametrize the couplings.
| $m_H$ [GeV] | 130 | 140 | 150 | 160 | 170 | 180 | 200 | 250 | 300 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $\sqrt{\frac{\Gamma_Y}{\Gamma_{SM}}}$ | 0.093 | 0.106 | 0.116 | 0.092 | 0.106 | 0.066 | 0.102 | 0.284 | 0.368 |
| $\sqrt{\frac{\Gamma_P}{\Gamma_{SM}}}$ | 0.106 | 0.117 | 0.125 | 0.123 | 0.126 | 0.102 | 0.146 | 0.156 | 0.121 |

Table 2

Ratio of the roots of the total widths of the pure states for various Higgs masses $m_H$. These ratios can be used to scale the constants $P$ and $Y$ such, that the non standard model couplings are of the same strength as the standard model coupling.

Any self consistent interpretation of the parameters is equally valid, and corresponds in general to a linear combination of the above couplings. In specific models for anomalous couplings a different parametrization and normalization might be preferred.

### 3 Results

We use the full information from the three fold differential cross-section by constructing the following likelihood function:

$$L(X, P) = \sum_{k \in \text{events}} \log \frac{M^2(\phi_k, \theta^k_1, \theta^k_2, P, Y, X = 1)}{\int M^2(\phi, \theta_1, \theta_2, P, Y, X = 1) d\phi d\cos \theta_1 d\cos \theta_2} \quad (4)$$

where $M^2$ is the squared matrix element evaluated at leading order. The value of $X$ is always fixed to the SM value of 1, since we want to measure small contributions from non-standard couplings. By maximising the likelihood we expect to find a value of zero for $P'$ and $Y'$. In order to demonstrate the potential of measuring these parameters with Atlas we show contour plots of the expected exclusion limits (see figure 1 and 2). The full luminosity of 300 fb$^{-1}$ has been used for all plots. The background has been statistically subtracted where the distribution of the background considered in this study was computed with Pythia. The distortion of the signal is not negligible, but since the contributions of the non standard model couplings are small the distortions don’t vary much. Therefore the expected likelihood distributions are affected only slightly by the detector effects. A remarkable feature of the contour-plots is the V-form in the $Y - P$ plane. This form is understandable, because a combination of $Y$ and $P$ couplings behaves very similar to the standard model coupling $X$. 
Fig. 1. Expected measurement of $P'/X$ and $Y'/X$ for masses of the Higgs of 140 GeV and 150 GeV. The quality of the measurement is mainly limited by statistics.

Fig. 2. Expected measurement of $P'/X$ and $Y'/X$ for masses of the Higgs of 200 GeV and 250 GeV. The much higher number of events allows for a much better measurement of the coupling structure above the ZZ threshold.

4 Conclusion

In this letter we described the analysis of the measurement of the $HZZ$ coupling structure at the LHC using the full information of the differential cross section $d\sigma/d\cos\theta_1 d\cos\theta_2 d\phi$. In contrast to other studies we include possible mixings between the different couplings. Using the full luminosity of 300 fb$^{-1}$ we are able to establish strong bounds on the hypothetical coupling constants $Y, P$ of the order 0.1 for a Higgs mass above the ZZ threshold. Below the threshold the results are limited by statistics. The results are conservative,
since we worked at LO only. An inclusion of K-factors is likely to improve the results by a factor of roughly $\sqrt{K}$. This analysis provides the necessary framework to perform the measurement of the HZZ coupling structure once a Higgs boson-like particle has been found at the LHC.

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