WORK PROJECT REPORT
Search for degenerate Higgs bosons

Jaana Heikkilä
supervisors: André David, Giovanni Petrucciani

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Abstract

Degenerate Higgs bosons have been searched as a summer student project. The goal was to implement an algorithm which would help to understand if there could be two Higgs bosons with very similar masses from the matrix of measured signal strengths $(\sigma \cdot B)_{\text{meas.}}/(\sigma \cdot B)_{\text{SM}}$ in different final states. The statistical compatibility of the observed data with a matrix of rank 1 has been evaluated. Using CMS data from the $\gamma\gamma$ and W^+W^- decay channels, a result compatible with a single Higgs boson at the level of 38% is obtained. A generalization of the algorithm to allow using all available data in the 5x4 signal strength matrix is also presented.

Contents

1 Purpose

The purpose of this report is to explain what are the tools in the search of degenerate Higgs bosons and how the search has been done. The goal was to implement an algorithm which would help to understand if there could be two Higgs bosons with very similar masses and apply it to all available data.

2 Theory

The cross section describes the likelihood of interaction between particles. The branching ratio is used to express the probability for the Higgs boson to decay to the given final state.

Let us consider a 2x2 matrix. The rows of this matrix represent two production modes, gluon fusion and vector boson fusion, respectively. The columns represent two decay modes, two photons and two W bosons. Every element of the 2x2 matrix is the ratio between the observed signal S_{obs} and the expected signal S_{exp}. The ratio has been written in terms of the cross section and the branching ratio

$$\frac{S_{\mathrm{obs}}}{S_{\mathrm{exp}}} = \frac{N_{\mathrm{obs}} - Bkg}{S_{\mathrm{exp}}} = \frac{(\sigma B)_{\mathrm{meas.}} LA\epsilon}{(\sigma B)_{\mathrm{SM}} LA\epsilon} = \frac{(\sigma B)_{\mathrm{meas.}}}{(\sigma B)_{\mathrm{SM}}}, \tag{1}$$

where N_{obs} stands for the observed number of events, Bkg for the expected background, L for integrated luminosity, A for acceptance and ϵ for efficiency. $(\sigma B)_{\mathrm{meas.}}$ stands for the measured cross section times branching ratio for Higgs bosons and $(\sigma B)_{\mathrm{SM}}$ for the corresponding expectation from the standard model.

The 2x2 matrix has been filled by using equation (1), but now an abbreviation has been used, i.e.

$$\frac{(\sigma B)_{\mathrm{meas.}}}{(\sigma B)_{\mathrm{SM}}} = \sigma B, \tag{2}$$

and therefore the matrix has been written in the form

	H$\gamma\gamma$	HW^+W^-
ggH	$\sigma_{gg} B_{\gamma\gamma} \pm \Delta\sigma_{gg} B_{\gamma\gamma}$	$\sigma_{gg} B_{WW} \pm \Delta\sigma_{gg} B_{WW}$
qqH	$\sigma_{VBF} B_{\gamma\gamma} \pm \Delta\sigma_{VBF} B_{\gamma\gamma}$	$\sigma_{VBF} B_{WW} \pm \Delta\sigma_{VBF} B_{WW}$

(3)

where σ_{gg} stands for the cross section of the gluon fusion, σ_{VBF} for the cross section of the vector boson fusion, $B_{\gamma\gamma}$ for branching ratio of two photons and B_{WW} for branching ratio of two W bosons.

It has been suggested that the number of resonances can be determined from a double ratio of the elements of the matrix [1]. The double ratio ρ has been defined [2] as

$$\rho = \frac{\sigma_{gg} B_{\gamma\gamma}}{\sigma_{gg} B_{WW}} \frac{\sigma_{VBF} B_{WW}}{\sigma_{VBF} B_{\gamma\gamma}}. \tag{4}$$

If there is one resonance, the expected value of ρ is 1 which means the matrix has a rank 1. If there is more than one resonance, the expected value of the double ratio ρ is arbitrary and the rank in general is 2. However, since there are four production modes and five analysed decay modes, the 2x2 matrix is not enough - a 5x4 matrix has to be defined in order to describe the whole situation.

3 The 5x4 matrix and the double ratio

The real 5x4 matrix of production tags and decay modes has been studied in CMS, Moriond 2013 [3] and a few new analyses have been added [4]; [5]; [6]; [7]; [8]:

	H$\gamma\gamma$	HW^+W^-	HZZ	H$\tau^+\tau^-$	H$b\bar{b}$
ggH	0.70 ± 0.31	0.73 ± 0.21	0.86 ± 0.29	0.77 ± 0.56	–
qqH	1.01 ± 0.58	0.60 ± 0.51	1.24 ± 0.72	1.42 ± 0.67	0.70 ± 1.40
VH	0.57 ± 1.24	0.51 ± 1.10	–	0.98 ± 1.59	1.00 ± 0.50
ttH	-0.20 ± 2.15	–	–	-0.73 ± 5.69	0.85 ± 2.44

Calculating the rank of this 5x4 matrix is impossible because of the missing elements. However, if the matrix has rank 1, also its submatrices must have rank 1. In order to calculate the double ratio ρ, all the possible 2x2 matrices have been analysed. For this purpose a program has been written. The program goes through all the possible 2x2 matrices and calculates the double ratio and the double ratio's uncertainty. The uncertainty of the double ratio ρ for the matrix (3) has been estimated using

$$\Delta\rho = |\rho| \sqrt{\left(\frac{\Delta\sigma_{gg} B_{\gamma\gamma}}{\sigma_{gg} B_{\gamma\gamma}}\right)^2 + \left(\frac{\Delta\sigma_{VBF} B_{\gamma\gamma}}{\sigma_{VBF} B_{\gamma\gamma}}\right)^2 + \left(\frac{\Delta\sigma_{gg} B_{WW}}{\sigma_{gg} B_{WW}}\right)^2 + \left(\frac{\Delta\sigma_{VBF} B_{WW}}{\sigma_{VBF} B_{WW}}\right)^2}. \tag{5}$$

All the ratios which have the uncertainty under 200 % are listed below in table (1).

Later on the double ratio ρ and its estimated uncertainty $\Delta\rho$ in the each case have been studied in a more sophisticated way. The case (ggH, qqH $\to$ $\gamma\gamma$, W^+W^-) has been selected as the most promising one for the analysis because it apparently has the smallest uncertainty.

The production modes	The decay modes	$\rho \pm \Delta\rho$
ggH, qqH	$\gamma\gamma$, W^+W^-	0.57 ± 0.66
ggH, qqH	$\gamma\gamma$, ZZ	1.00 ± 0.99
ggH, qqH	$\gamma\gamma$, $\tau^+\tau^-$	1.28 ± 1.45
ggH, qqH	W^+W^-, ZZ	1.76 ± 1.98
ggH, qqH	ZZ, $\tau^+\tau^-$	1.28 ± 1.41

Table 1: The 2x2 submatrices and their double ratios which have the uncertainty under 200 %.

4 Statistical treatment

Calculating the double ratio is not straightforward because of the uncertainties. Therefore the statistical compatibility of the observed data with a matrix of the rank 1 has been evaluated. A likelihood function $L = L(\rho)$ takes into account the observation(s) as the parameter is changed. For every case the best fit value of ρ, denoted as $\hat{\rho}$, has been determined by maximizing the likelihood function $L(\rho)$. By comparing the likelihood function L at the given value of ρ and at the best fit value of ρ, denoted as $\hat{\rho}$, the test statistic $q = q(\rho)$ has been defined as the profile likelihood ratio

$$q(\rho) = -2 \ln \frac{L(\rho)}{L(\hat{\rho})}. \tag{6}$$

A p-value is obtained from the fact that approximately

$$q(\rho = 1) = \chi^2(1 \text{ d.o.f}), \tag{7}$$

which is a test against the hypothesis of the rank 1, i.e. at least one resonance.

In order to test the data against the hypothesis of the rank 1, a parametrisation of the expected signal yield has been developed. The model used for this purpose has been written by using the definition of the double ratio ρ (4) and the model is following:

$$\begin{array}{ccc} & \mathrm{H}\gamma\gamma & \mathrm{H}W^+W^- \\ \hline \mathrm{ggH} & \mu_{\gamma\gamma} & \mu_{WW} \\ \mathrm{qqH} & \lambda \cdot \mu_{\gamma\gamma} & \lambda \cdot \mu_{WW} \cdot \rho \end{array} \tag{8}$$

where $\mu_{\gamma\gamma}$ and μ_{WW} stand for the signal strengths in the gluon fusion for the two decay modes and λ for the relative scaling factor between the two production modes.

5 Simplified data cards

Before using the real data, simplified ("toy") data cards have been used as a tool. The toy data cards for the each submatrix element have been created as counting experiments so that they match the observed signal strength and its uncertainty. For example the data card of element ggH $\rightarrow$ H$\gamma\gamma$(untagged) includes the number of observed events $N = 33.096$, expected total signal $S = 18.709$ and background $B = 20$. These simplified data cards have few important features.

5.1 Mixing between production modes

The production channels are mixed, i.e. a part of the observed $0j$ tagged signal (mostly from the gluon fusion) is from the vector boson fusion, and also a part of the observed $2j$ tagged signal (mostly from the vector boson fusion) is from the gluon fusion. Approximate assumptions about the signal composition in the different final states were made from the simulations and the contamination level can be seen in table (2).

In reality, the composition in the $\gamma\gamma$ channel is more complex than in the approximation. There are several subcategories in $0j$ and $2j$ channels, categories which have different mixtures. In the real data cards there is also signal from the VH (the Higgs–strahlung), which in some subcategories looks like the signal from the vector boson fusion. These are the reasons why the simplified data cards do not correspond to the real data cards very well.

	hgg_0j	hgg_2j	hww_0j	hww_2j	hzz_0j	hzz_2j	htt_0j	htt_2j
ggH	0.90	0.30	0.95	0.15	0.90	0.80	0.80	0.20
qqH	0.10	0.70	0.05	0.85	0.10	0.20	0.20	0.80

Table 2: The mixing levels of the gluon fusion and the vector boson fusion in each decay mode mentioned in the list of 2x2 matrices. Here (0) stands for ggH-dominated and (2) for di-jet tagged.

5.2 Theoretical uncertainty

Theoretical uncertainties have been approximately taken into account in the simplified data cards. The theoretical uncertainty is modelled as a log-normal distribution, which multiplies the event yield. The systematic error assumed on the gluon fusion cross section is 10 % and 30 % in 0 jets and 2 jets final states, respectively. The systematic uncertainty on the vector boson fusion is much smaller, and has been neglected.

5.3 Fit for the double ratio ρ using the simplified data card

The best fit value of the double ratio ρ is $\hat{\rho} = 0.43\ ^{+2.07}_{-0.43}$ as shown in figure (1).

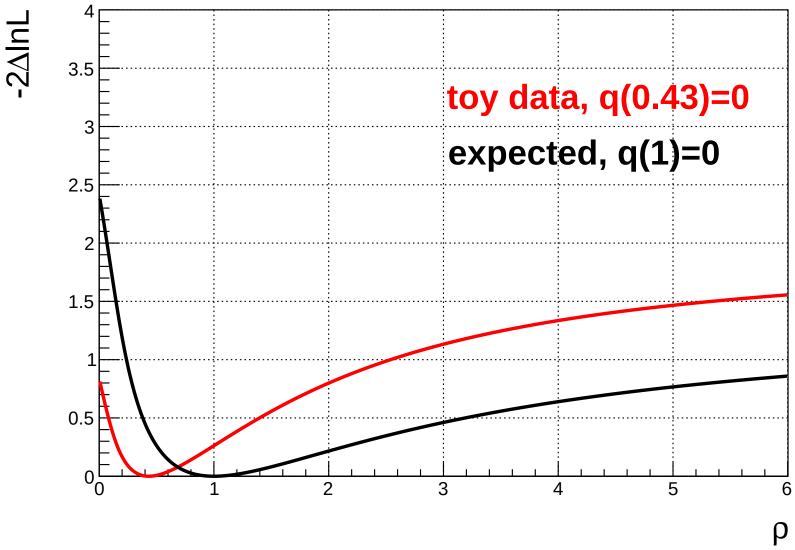

Figure 1: Case (ggH, qqH $\rightarrow \gamma\gamma$, W^+W^-). Fit for the double ratio ρ (best fit value $\hat{\rho} = 0.43$). The p-value of the hypothesis $\rho = 1$ is in this case 0.61 - this means that there is approximately 61 % probability to measure q(1)$>$ 0.26 if the matrix has rank 1.

6 Real data cards from Moriond 2013 combination

After going through the case of the 2x2 matrices with toy data cards, it is natural to move on to the real data cards. Since these real data cards include all four production modes, the model has to be modified so that it takes into account all of them; the gluon fusion, the vector boson fusion, the Higgs–strahlung and the ttH associated production:

$$\begin{array}{c|cc} & \mathrm{H}\gamma\gamma & \mathrm{H}W^+W^- \\ \hline \mathrm{ggH} & \mu_{\gamma\gamma} & \mu_{WW} \\ \mathrm{qqH} & \lambda \cdot \mu_{\gamma\gamma} & \lambda \cdot \mu_{WW} \cdot \rho \\ \mathrm{VH} & \lambda_{\mathrm{v}} \cdot \mu_{\gamma\gamma} & \lambda_{\mathrm{v}} \cdot \mu_{WW} \cdot \rho_{\mathrm{v}} \\ \mathrm{ttH} & \lambda_{\mathrm{t}} \cdot \mu_{\gamma\gamma} & \lambda_{\mathrm{t}} \cdot \mu_{WW} \cdot \rho_{\mathrm{t}} \end{array} \tag{9}$$

The only parameter of interest is ρ: $\mu_{\gamma\gamma}$, μ_{WW}, λ, λ_{v} and ρ_{v} have been profiled. In this case the production mode ttH has not been scaled, i.e. it has been set $\lambda_{\mathrm{t}} \cdot \mu_{\gamma\gamma} = \lambda_{\mathrm{t}} \cdot \mu_{WW} \cdot \rho_{\mathrm{t}} = 1$ like in the standard model.

The best fit value of the double ratio ρ is $\hat{\rho} = 0.30\ ^{+0.85}_{-0.26}$ as shown in figure (2).

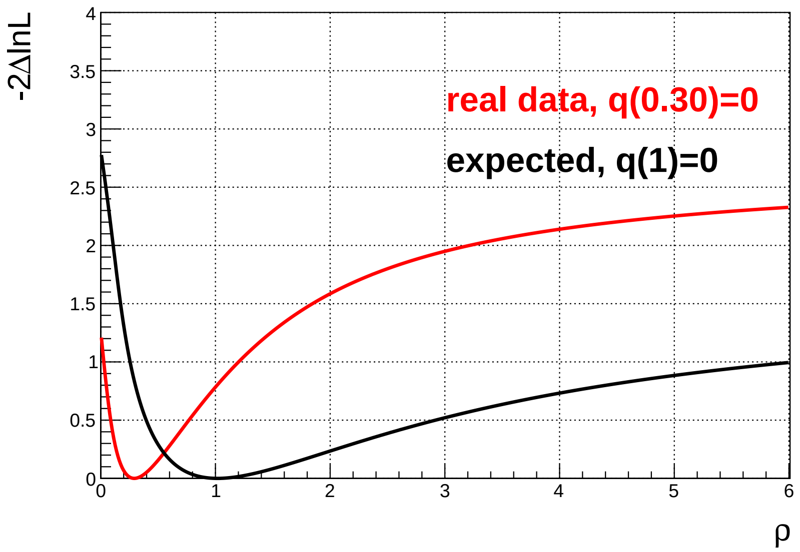

Figure 2: Case (ggH, qqH $\to \gamma\gamma$, W^+W^-). Fit for the double ratio ρ (best fit value $\hat{\rho} = 0.30$). The p-value is 0.38. Parameters $\mu_{\gamma\gamma}$, μ_{WW}, λ, λ_v and ρ_v have been profiled.

7 Exploiting all the available information

The ratio between the production modes is not dependent of the decay mode if there is only Higgs boson. If there is only one resonance, the 5x4 signal strength matrix can be decomposed as a tensor product of two vectors (μ_i) and $(1, \lambda, \lambda_\mathrm{v}, \lambda_\mathrm{t})$.

In order to test if the matrix of the signal strengths follow such decomposition, two new models have been defined. These new models take into account three other decay modes: ZZ, $\tau^+\tau^-$ and $b\bar{b}$. The first model uses the most general rank 1 matrix mentioned above and the second model the most general 5x4 matrix.

1) μ_i, λ, λ_v and λ_t (the most general rank 1 matrix)

	H$\gamma\gamma$	HW^+W^-	HZZ	H$\tau^+\tau^-$	H$b\bar{b}$
ggH	$\mu_{\gamma\gamma}$	μ_{WW}	μ_{ZZ}	$\mu_{\tau\tau}$	$\mu_{b\bar{b}}$
qqH	$\lambda \cdot \mu_{\gamma\gamma}$	$\lambda \cdot \mu_{WW}$	$\lambda \cdot \mu_{ZZ}$	$\lambda \cdot \mu_{\tau\tau}$	$\lambda \cdot \mu_{b\bar{b}}$
VH	$\lambda_\mathrm{v} \cdot \mu_{\gamma\gamma}$	$\lambda_\mathrm{v} \cdot \mu_{WW}$	$\lambda_\mathrm{v} \cdot \mu_{ZZ}$	$\lambda_\mathrm{v} \cdot \mu_{\tau\tau}$	$\lambda_\mathrm{v} \cdot \mu_{b\bar{b}}$
ttH	$\lambda_\mathrm{t} \cdot \mu_{\gamma\gamma}$	$\lambda_\mathrm{t} \cdot \mu_{WW}$	$\lambda_\mathrm{t} \cdot \mu_{ZZ}$	$\lambda_\mathrm{t} \cdot \mu_{\tau\tau}$	$\lambda_\mathrm{t} \cdot \mu_{b\bar{b}}$

2) μ_i, λ^i, λ_{v}^i and λ_{t}^i (the most general 5x4 matrix)

	$\mathrm{H}\gamma\gamma$	$\mathrm{H}W^+W^-$	$\mathrm{H}ZZ$	$\mathrm{H}\tau^+\tau^-$	$\mathrm{H}b\bar{b}$
ggH	$\mu_{\gamma\gamma}$	μ_{WW}	μ_{ZZ}	$\mu_{\tau\tau}$	$\mu_{b\bar{b}}$
qqH	$\lambda^{\gamma\gamma}\cdot\mu_{\gamma\gamma}$	$\lambda^{WW}\cdot\mu_{WW}$	$\lambda^{ZZ}\cdot\mu_{ZZ}$	$\lambda^{\tau\tau}\cdot\mu_{\tau\tau}$	$\lambda^{b\bar{b}}\cdot\mu_{b\bar{b}}$
VH	$\lambda_{\mathrm{v}}^{\gamma\gamma}\cdot\mu_{\gamma\gamma}$	$\lambda_{\mathrm{v}}^{WW}\cdot\mu_{WW}$	$\lambda_{\mathrm{v}}^{ZZ}\cdot\mu_{ZZ}$	$\lambda_{\mathrm{v}}^{\tau\tau}\cdot\mu_{\tau\tau}$	$\lambda_{\mathrm{v}}^{b\bar{b}}\cdot\mu_{b\bar{b}}$
ttH	$\lambda_{\mathrm{t}}^{\gamma\gamma}\cdot\mu_{\gamma\gamma}$	$\lambda_{\mathrm{t}}^{WW}\cdot\mu_{WW}$	$\lambda_{\mathrm{t}}^{ZZ}\cdot\mu_{ZZ}$	$\lambda_{\mathrm{t}}^{\tau\tau}\cdot\mu_{\tau\tau}$	$\lambda_{\mathrm{t}}^{b\bar{b}}\cdot\mu_{b\bar{b}}$

If the matrix has rank 1, the rows of these two models are the same, i.e. $\lambda \equiv \lambda^i$, $\lambda_{\mathrm{v}} \equiv \lambda_{\mathrm{v}}^i$ and $\lambda_{\mathrm{t}} \equiv \lambda_{\mathrm{t}}^i$. In this case the profile likelihood ratio is

$$q_\lambda = -2\ln\frac{L(\mathrm{data}|\lambda^i = \hat{\lambda},\ \lambda_{\mathrm{v}}^i = \hat{\lambda}_{\mathrm{v}},\ \lambda_{\mathrm{t}}^i = \hat{\lambda}_{\mathrm{t}})}{L(\mathrm{data}|\hat{\lambda}^i, \hat{\lambda}_{\mathrm{v}}^i, \hat{\lambda}_{\mathrm{t}}^i)}, \tag{10}$$

which can be written in the form

$$\begin{aligned} q_\lambda &= q_2(\lambda^i = 1, \lambda_{\mathrm{v}}^i = 1, \lambda_{\mathrm{t}}^i = 1) - q_1(\lambda = 1, \lambda_{\mathrm{v}} = 1, \lambda_{\mathrm{t}} = 1) \\ &= -2\ln\frac{L(\mathrm{data}|\lambda^i = 1, \lambda_{\mathrm{v}}^i = 1, \lambda_{\mathrm{t}}^i = 1)}{L(\mathrm{data}|\hat{\lambda}^i, \hat{\lambda}_{\mathrm{v}}^i, \hat{\lambda}_{\mathrm{t}}^i)} + 2\ln\frac{L(\mathrm{data}|\lambda = 1, \lambda_{\mathrm{v}} = 1, \lambda_{\mathrm{t}} = 1)}{L(\mathrm{data}|\hat{\lambda}, \hat{\lambda}_{\mathrm{v}}, \hat{\lambda}_{\mathrm{t}})}. \end{aligned} \tag{11}$$

The analysis with these two models is ongoing.

8 Conclusion

A method to test for the presence of multiple Higgs bosons has been developed. Using CMS data from the W^+W^- and $\gamma\gamma$ decay channels, we obtain a result compatible with a single Higgs boson at the level of 38%.
The analysis is now being done using the other production and decay modes. This project will be continued and expanded into a Master's thesis.

References

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