

# Upper limit for High mass $X \rightarrow WW$ search

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## Abstract

## 1 Introduction

In this report we will study the statistical approach to the upper limit computation for a high energy physics search for a new particle. We will use data from the 2015 run of the CMS experiment at the LHC and the corresponding Monte Carlo (MC) simulations.

We will search for a new signal in the  $WW \rightarrow 2l2\nu$  final state. This channel is also a decay channel for the Standard Model Higgs boson (H). We will however search for an additional particle, named X in the following, that is supposed to be heavier than H. We will scan a wide range of masses for X and, if we do not find a compelling evidence for a signal, we will set an upper limit on the cross section of X.

## 2 The physics case

In this experience we will search for the existence of a new hypothetical high mass particle, named X. **We expect this particle to be a heavy variant of the Standard Model Higgs boson.** For this reason we hypothesize that X shares with H the production mechanism. This is a reasonable assumption that is verified in several new physics models. In particular we assume that X can be produced via two main production mechanisms, called gluon fusion (ggF) and vector boson fusion (VBF), represented by the diagrams in Fig. 1.

The details and precise meaning of the Feynman diagrams of Fig. 1 are not relevant for this exercise, the relevant piece of information is that two

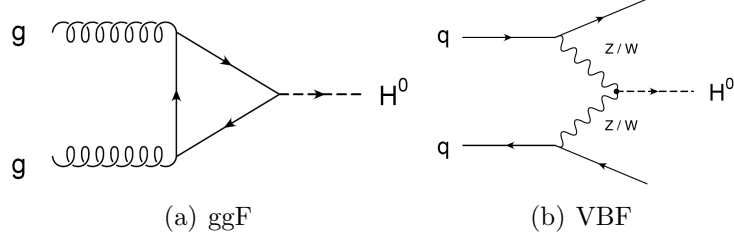


Figure 1: Feynmann diagrams of the two main production mechanisms for X.

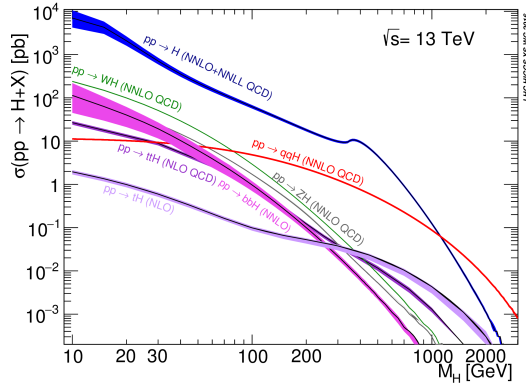


Figure 2: Standard model Higgs boson cross section as a function of the mass of the Higgs boson. The ggF mechanisms is labeled  $pp \rightarrow H$ , the VBF mechanism is labeled  $pp \rightarrow qqH$ . Also other, sub-leading mechanisms are reported, which we will neglect.

mechanisms are available and that they are marked by a substantial difference: **the ggF shows no other particles in the final state beyond X, the VBF has two quarks in addition to the X in the final state.** Although it should be noted that a precise calculation shows that additional particles in the form of hadronic jets can also arise in ggF, it remains true that events arising from the two mechanisms are different when it comes to the number of jets produced in addition to the X particle.

The production cross section for the Higgs boson as a function of its mass is reported in Fig. 2. Although we now know the mass of the Higgs boson to be 125 GeV, this plot is useful because it can be used as a model for the expected cross section for X.

We will assume that the cross section  $\sigma$  for each of the production channels of X scales with a common factor  $\mu$  of the corresponding Higgs boson cross section:

$$\sigma_{X[ggF,VBF]}(M) = \mu(M)\sigma_{H[ggF,VBF]}(M) \quad (1)$$

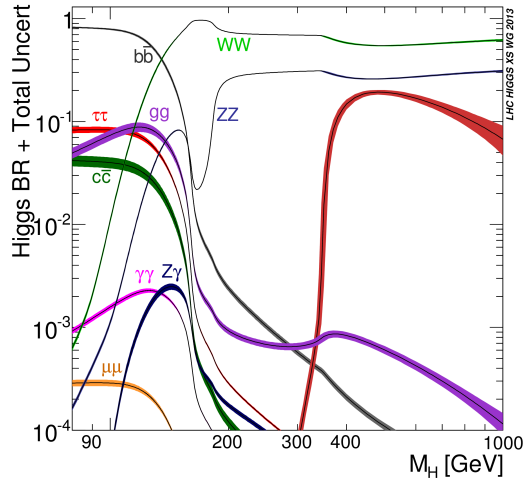


Figure 3: Standard model Higgs boson cross section as a function of the mass of the Higgs boson. The ggF mechanism is labeled  $pp \rightarrow H$ , the VBF mechanism is labeled  $pp \rightarrow qqH$ . Also other, sub-leading mechanisms are reported, but we will neglect them.

where  $M$  is the mass of  $X$ , and obvious meaning of the other symbols. This is a reasonable assumption, verified by several new physics models. We notice that **the relative importance of the VBF mechanism grows with the  $X$  mass**, and becomes dominant above  $\sim 1.5$  TeV.

We will assume that, like  $H$ , also  $X$  has several decay channels. We assume that  $X$  has the same branching ratios of  $H$ , which are summarized in Fig. 3. It should be noted that **the  $WW$  decay channel is the one with the highest branching ratio**.

### 3 Data sample and analysis strategy

Owing to the large branching fraction in the  $WW$  final state we choose this channel for our search. In other words we search for the decay  $X \rightarrow WW$ . The  $W$  bosons are themselves unstable. 30% of the times a  $W$  boson decays to a charged lepton (electron, muon, tauon) and a neutrino (10 % for each of the three lepton species). The remaining 70% of the times the  $W$  boson decays to a pair of hadrons. In this exercise we will concentrate on the leptonic decays of the  $W$  bosons. The reason of this choice will become clearer when we discuss backgrounds, but let us mention already that requiring leptons in the final state allows a dramatic reduction of background processes. To summarise, **we search for the  $H \rightarrow WW \rightarrow 2l2\nu$  decay chain**.

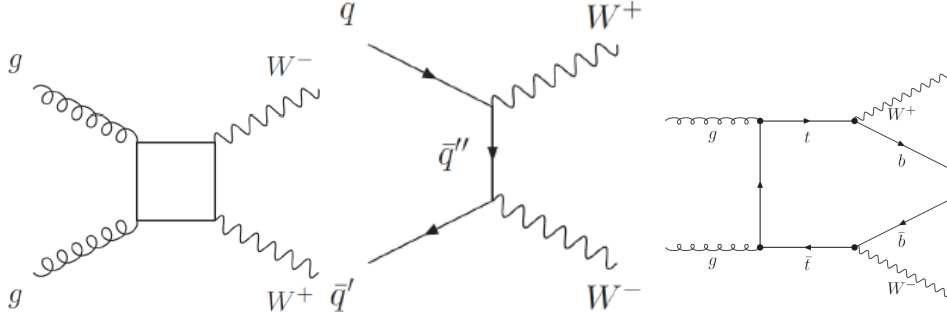


Figure 4: Gluon initiated (a) and quark initiated (b) WW. Top pair production (c).

We will use data collected by the CMS experiment in the 2015 data taking at the LHC. These data correspond to an integrated luminosity of  $2.3 \text{ fb}^{-1}$ . We will base our analysis on data reconstructed with the official CMS software and Simulations for both the signal and the background processes. These data come in the form of ROOT trees.

For each event the tree stores several event variables, in particular:

- reconstructed leptons kinematic variables;
- the reconstructed missing transverse energy;
- the reconstructed jet kinematic variables.
- several weights, used both to improve the Data/Simulation agreement and to normalize the simulation to the data luminosity.

### 3.1 Main backgrounds

A background process in a high energy physics analysis is a physics process that yields a final state that resembles that of the signal. In the case of this analysis there are two main background processes:

- production of two W bosons without an intermediate X;
- production of a pair of top quarks,  $t\bar{t}$ . The top quark decays to a b quark and a W boson.

The Feynman diagrams of these two processes are reported in Fig. 4 for the interested reader.

We apply a series of cuts to reduce their contribution as much as possible.  $t\bar{t}$  is reduced by requiring that jets in the event are not compatible with being

originated from b quarks, using dedicated jet-tagging techniques. WW is reduced with kinematic cuts on the leptons.

Other subleading sources of background originate from processes in which at least one of the leptons is not a real lepton, but is identified as such by the reconstruction algorithms. The control of these backgrounds is a crucial part of the analysis, but is beyond the scope of this exercise. The cuts to be applied will be provided by the teachers.

### 3.2 Main discriminating variable

After the selection cuts mentioned above we end up with a sample that is primarily composed of WW and  $t\bar{t}$ . In order to further discriminate a possible signal we use a kinematic variable called  $m_{T,i}$ . This variable is the invariant mass of the 4-momentum resulting from the sum of the two lepton 4-momenta and the MET 4-momentum. Since we are unable to reconstruct the longitudinal component of the neutrinos momenta, this variable is the closest approximation of the resonance invariant mass that we can reconstruct in a signal event, and it retains a significant discriminating power with respect to backgrounds.

The distribution of  $m_{T,i}$  is shown in Fig. 5 after the selection cuts. The data points are shown on top of the stack of the backgrounds. The shape of a signal for X mass of 1 TeV is also shown (multiplied by 10). The rightmost bin of each distribution is an overflow bin. The fact that the signal shape does not peak at 1 TeV is due to  $m_{T,i}$  lacking the contribution from the longitudinal momenta of neutrinos.

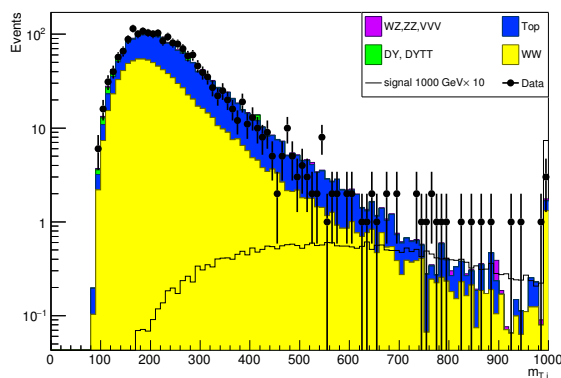


Figure 5:  $m_{T,i}$  in data and simulation for 2015 data after selection cuts.

## Exercise 1:

**Write a code that builds the stack of backgrounds to obtain a plot similar to Fig. 5.**

A set of root files is provided, together with a root macro (`HWWYields.C`) implementing selection cuts.

Each root file contains a root tree named `latino`. This tree holds several variables, including  $m_{T,i}$  in a branch called `mTi`.

Eight data files are provided, corresponding to two distinct data taking periods (called `Run2015C` and `Run2015D`) and four triggers. Data from CMS are in fact divided into different streams depending on the triggers each event fires. In this analysis we use events with at least two electrons (`DoubleEG`), at least two muons (`DoubleMu`), at least an electron and a muon (`MuonEG`) or at least a muon (`SingleMuon`). The latter is used only to recover an inefficiency in the other triggers.

Simulated events (MC) are produced for several physics processes, including  $t\bar{t}$ ,  $WW$ ,  $Z \rightarrow \tau\tau$ , and other subleading processes. Simulated samples for different mass hypotheses for  $X$  are also provided. For each mass hypothesis two different files are provided, one containing the simulation of the  $ggF$  production mechanism and the other containing the simulation for the  $VBF$  production mechanism.

Simulated events are weighted with several weights that are aimed at bringing data and MC in close agreement. We will not discuss these weight in detail. We will just discuss an important weight contained in the branch named `baseW`. This variable is used to equalize the luminosity of all samples to 1/fb.

Running `HWWYields.C` results in a root file (`yields.root`) containing one histogram for each background, one for each signal and one for the data. The variable plotted and the binning are controlled in the first few lines of `HWWYields.C`.

Please write a root macro that builds a stack of all the backgrounds, superimposes the data and one signal for reference.

## 3.3 Cut based analysis

In order to check whether the data are consistent with the signal+background hypothesis or with the background only hypothesis, we can proceed to counting events passing our selection. Let  $N_{obs}$  be the data events after the selection,  $\nu_b$  be the expected number of background events and  $\nu_s$  be the expected number of signal events for an  $X$  signal with mass  $M$ . We expect  $N_{obs}$  to follow the Poisson statistics with an average of  $\nu_b + \nu_s$  in the signal+background

hypothesis and  $\nu_b$  in the background only hypothesis.

The best estimate that we can give of the number of signal events, based on a single experiment, is

$$\hat{\nu}_s = N_{obs} - \nu_b \quad (2)$$

where the dependency on the mass hypothesis is there to remind us that the analysis cuts can be different depending on the mass of the signal we search for.

In order to understand whether the obtained value of  $\hat{\nu}_s$  is significantly different from 0 we should compare it with the statistical fluctuation of the expected background. Only if  $\hat{\nu}_s$  is larger than several standard deviations (5) of the expected background we can claim a discovery.

Following this discussion we are left with an open question: should we add any other selection cuts to our selection to improve the analysis sensitivity to a signal?

## Exercise 2

**For each X mass hypothesis find the cut on  $m_{T,i}$  which maximises the sensitivity**

Fig. 5 shows that  $m_{T,i}$  has a good discriminating power. In particular if we only count events above a certain optimal value of  $m_{T,i}$  we should be able to improve the sensitivity to a signal.

The student should find, for each X mass hypothesis, the value of  $m_{T,i}$  ( $m_{T,i}^{cut}$ ) such that by integrating events with  $m_{T,i} > m_{T,i}^{cut}$  the ratio of expected number of signal events  $\nu_s$  and the statistical fluctuation of background events  $\sqrt{\nu_b}$  ( $\nu_s/\sqrt{\nu_b}$ ) is maximised.

### 3.4 Upper limit with approximate formulae

Upon completion of Exercise 2 the student has found the optimal value in  $m_{T,i}$  where one should cut in order to find a possible signal. The optimal position of the cut depends on the mass of the hypothesized signal.

We now aim at finding the upper limit for each mass hypothesis. We refer to Cowan's book equation 9.39. The upper limit at 95% confidence level on the number of signal events ( $\nu_{up}$ ) can be found as:

$$\nu_{up} = \hat{\nu}_s + \delta_{\hat{\nu}_s} \cdot \Phi^{-1}(0.95) \quad (3)$$

where  $\hat{\nu}_s$  is given by Eq. 2,  $\delta_{\hat{\nu}_s}$  is the error on  $\hat{\nu}_s$ ,  $\Phi^{-1}$  is the inverse cumulative distribution of the Gaussian.

Eq. 3 holds under the assumption that the distribution of  $\hat{\nu}_s$  is **Gaussian**. However  $\hat{\nu}_s$ , as defined in Eq. 2 comes as the difference between a random variable distributed according to Poisson distribution ( $N_{obs}$ ) and a number. The assumption that  $\hat{\nu}_s$  is Gaussian is only valid in case  $N_{obs}$  has a relatively large expectation value, so that the difference between Poisson and Gaussian distribution can be neglected.

How do we estimate  $\delta_{\hat{\nu}_s}$ ? If we know the number of expected background events with no error, then  $\delta_{\hat{\nu}_s} = \sqrt{N_{obs}}$ , following Poisson statistics.

However we usually have an uncertainty on the estimation of the number of background events  $\delta_{\nu_b}$ . This kind of uncertainty is systematic, contrary to the uncertainty on  $N_{obs}$ , which is statistical instead. It is not obvious how to combine the two uncertainties into  $\delta_{\hat{\nu}_s}$ .

In the following we will make a common choice, which consists in combining the two uncertainties as one would do if they were both statistical. It then follows that

$$\delta_{\hat{\nu}_s} = \sqrt{N_{obs} + \delta_{\nu_b}^2}. \quad (4)$$

Let us discuss in some more detail the meaning of our choice of summing in quadrature the genuinely statistical uncertainty on  $N_{obs}$  and the systematic uncertainty  $\delta_{\nu_b}$ . By doing this we are effectively expressing our degree of belief in our estimate of the background in the form of a Gaussian with average  $\nu_b$  and standard deviation  $\delta_{\nu_b}$ . Indeed, if you assume that the true value of the expected number of background events is distributed as a Gaussian of standard deviation  $\delta_{\nu_b}$  around the average  $\nu_b$ , then the variance of  $\hat{\nu}_s$  is indeed given by Eq. 4.

In other words we are weighting the probability that we are wrong about our estimate of the number of background events in a Gaussian way with respect to our best estimate  $\delta_{\nu_b}$ . It should be somewhat clear from the choice of words in the two past sentences that we are to some extent entering the realm of Bayesian probability, in that we are using a PDF, a Gaussian in this case, to measure how sure we are of our background estimate.

It should be clear that using a Gaussian to describe our degree of belief in the background estimate, as an effective way of modeling the systematic uncertainties is not the only option. Other systematic uncertainties may be better modeled by different PDFs, such as Uniform, or lognormal. It is in general a good practice (although not always done in practice) to test the robustness of a result against the (somewhat arbitrary) choice of the PDF that models the systematic uncertainties.



## Exercise 3

### Derive an upper limit on the signal strength $\mu$ using Eq. 3

Using the signal and background yields obtained from the mass dependent cuts of Exercise 2, the student should plot the expected and observed limit.

The systematic uncertainty on the background should be taken to be a (reasonable) 10% of  $\nu_b$ .

The expected limit is the limit you expect to put in the signal background only hypothesis. It can be derived very simply by assuming  $\hat{\nu}_s=0$ . This however does not give you any sense of how the statistical fluctuations in the number of observed events may affect the limit even in the background only hypothesis.

In order to have such an idea the student should make several “toy” experiment, i.e., they should simulate what the result of an experiment could be in a background only hypothesis. In our simple case this boils down to throwing several random numbers according to the Poisson distribution around  $\nu_b$ . Each random extraction would yield a number  $N_{obs}^i$ . For each  $N_{obs}^i$  the student should compute the upper limit according to Eq. 3. The expected limit can be extracted by taking the median of the limits obtained in all the toy extractions. Similarly a 1 and 2 sigma band can be extracted by taking the 2.5% percentile ( $2\sigma$  down), 34% ( $1\sigma$  down), 84% ( $1\sigma$  up), 97.5% ( $2\sigma$  up) of the distribution of expected limits from toys for each mass.

The observed limit is the limit obtained from data, using  $N_{obs}$  from data. The student should finally obtain a plot similar to the one shown in Fig. 6.

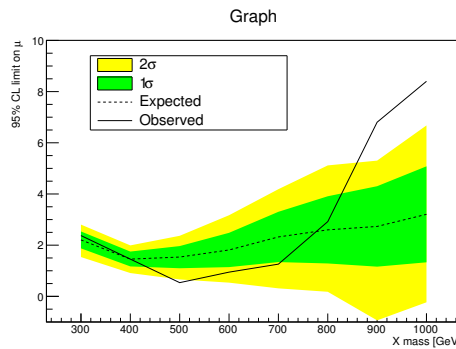


Figure 6: Expected and observed limit. The result of Exercise 3 should be something of this form.