Tests des Standardmodells der Teilchenphysik

Spezialfach Kern-Teilchen-Astrophysik

Tests of the Standard Model of Particles

Spring Semester 2018

Lecture 2

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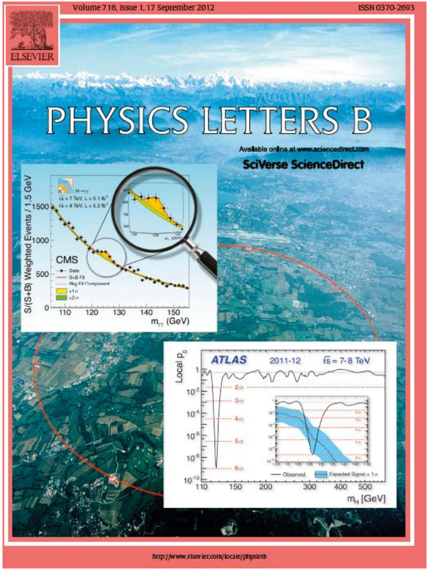
April 19, 2018

Overview

- The discovery of the Higgs boson
- Discovery channels
- Addendum - Statistics for Searches at the LHC in a nutshell



The discovery of the Higgs boson

In proton–proton collisions at a center-of-mass energy of $8\ \mathrm{TeV}$, the total production cross section for a Higgs boson with $m_H = 125\ \mathrm{GeV}$ is approximately $20\ \mathrm{pb}$.

The first observations of the Higgs boson were based on approximately $L_{\text{int}} = \int dtL = 20\ \mathrm{fb}^{-1}$ of data (ATLAS and CMS combined).

This data sample corresponded to a total of approximately $N = \sigma \times L_{\text{int}} = 400\ \mathrm{k}$ produced Higgs bosons.

Whilst this number might seem large, it is a tiny fraction of the total number of interactions recorded at the LHC, most of which involve the QCD production of multi-jet final states, and $Z + \mathrm{jets}$ and $W + \mathrm{jets}$ production.

Consequently, it is difficult to distinguish the decays of the Higgs boson producing final states with jets from the large Standard Model processes.

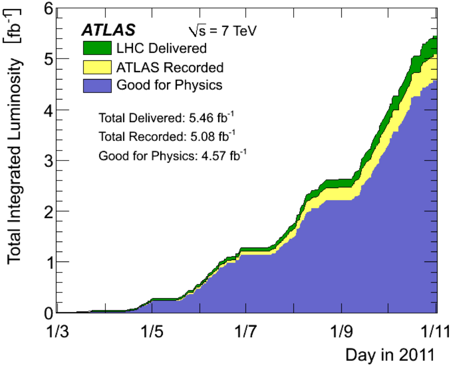
For this reason, the most sensitive searches for the Higgs boson at the LHC are in decay channels with distinctive final-state topologies, such as

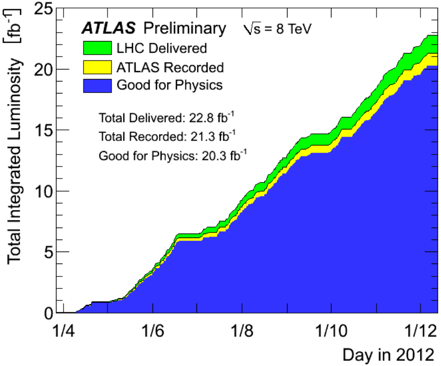
1. $H \to \gamma\gamma$
2. $H \to Z^* Z \to \ell^+ \ell^- \, \ell'^+ \ell'^-$ with $\ell = e$ or μ
3. $H \to W^* W \to e\nu_e \, \mu\nu_\mu$

These consider bosonic final states of the Higgs boson; the observation of the Higgs boson into fermionic channels was established only a year after.

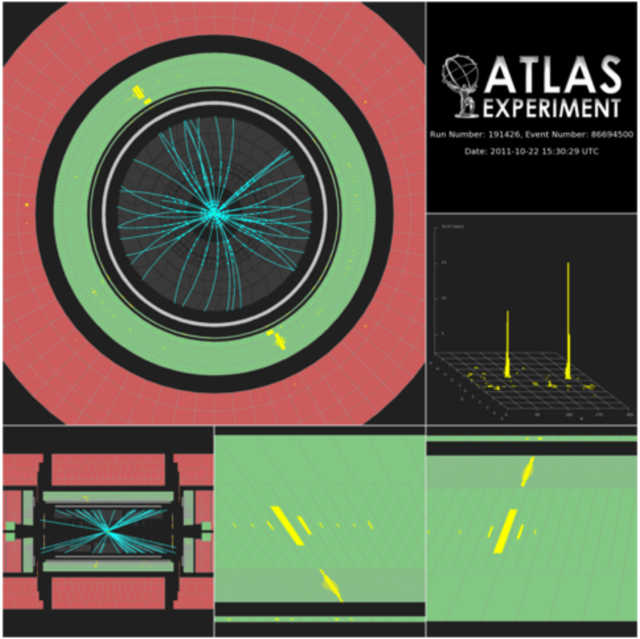
Despite the relatively low branching ratios for these decay modes, the experimental signatures are sufficiently clear for them to be distinguished from the backgrounds from other processes.

LHC data





Cumulative luminosity versus time delivered to (green), recorded by ATLAS (yellow), and certified to be good quality data (blue) during stable beams and for pp collisions at 7 and 8 TeV centre-of-mass energy in 2011 and 2012, respectively (ref).



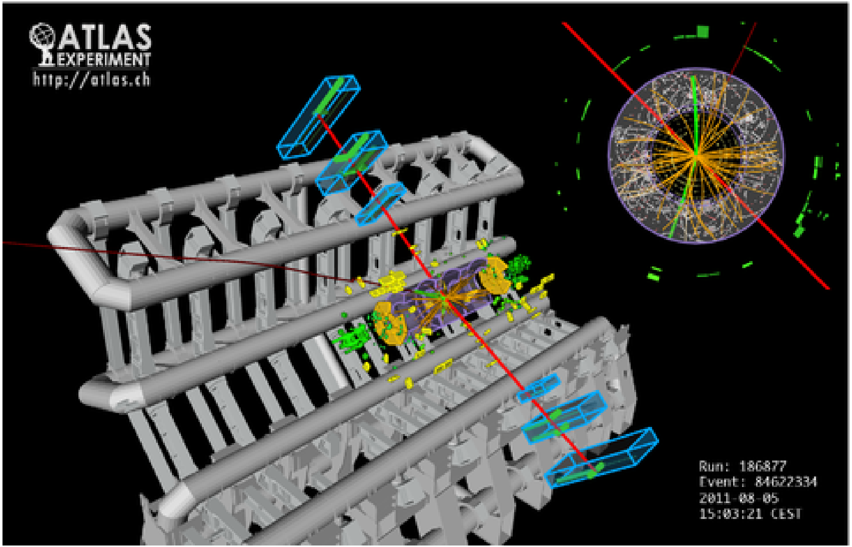
$H \to \gamma\gamma$ candidate event in ATLAS at $\sqrt{s} = 7$ TeV.

The leading photon has $E_T = 64.2$ GeV and $\eta = -0.34$.

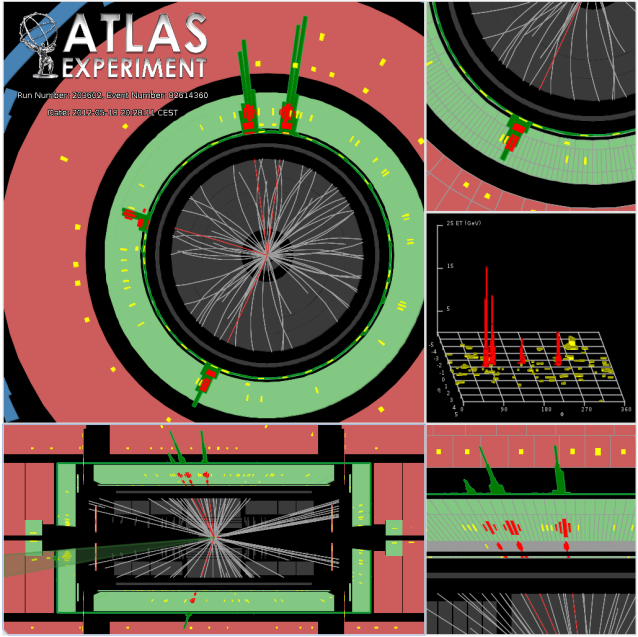
The subleading photon has $E_T = 61.4$ GeV and $\eta = -0.61$.

The measured diphoton mass is $m_{\gamma\gamma} = 126.6$ GeV.

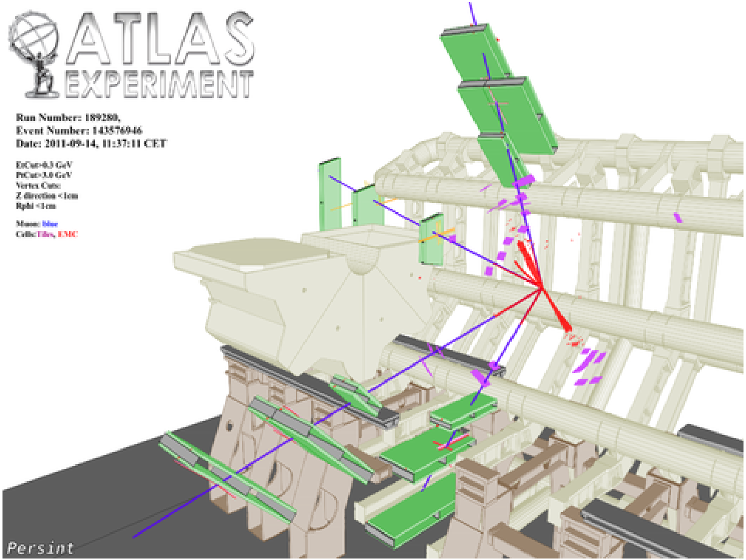
Only reconstructed tracks with $p_T > 1$ GeV, hits in the pixel and SCT layers and TRT hits with a high threshold are shown ATLAS-CONF-2011-161.



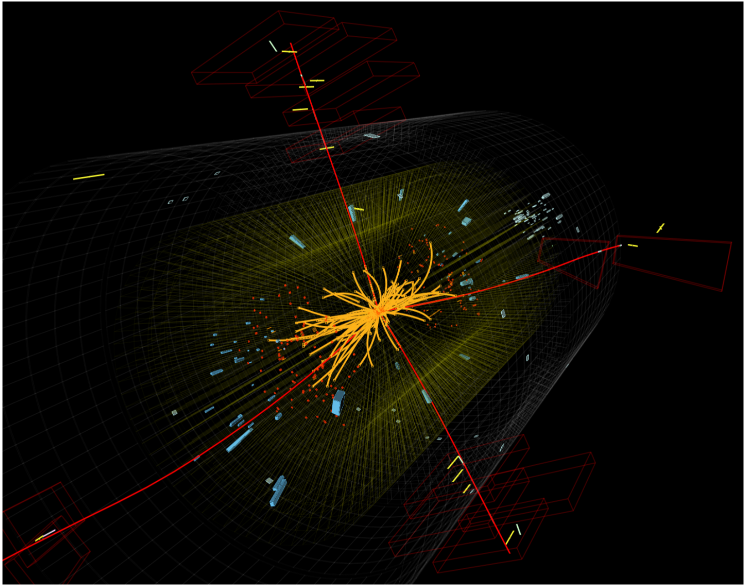
Event displays of a $2\mu\ 2e$ candidate event with reconstructed invariant mass $m = 123.6$ GeV. The masses of the lepton pairs are 89.3 GeV and 30.0 GeV, respectively.



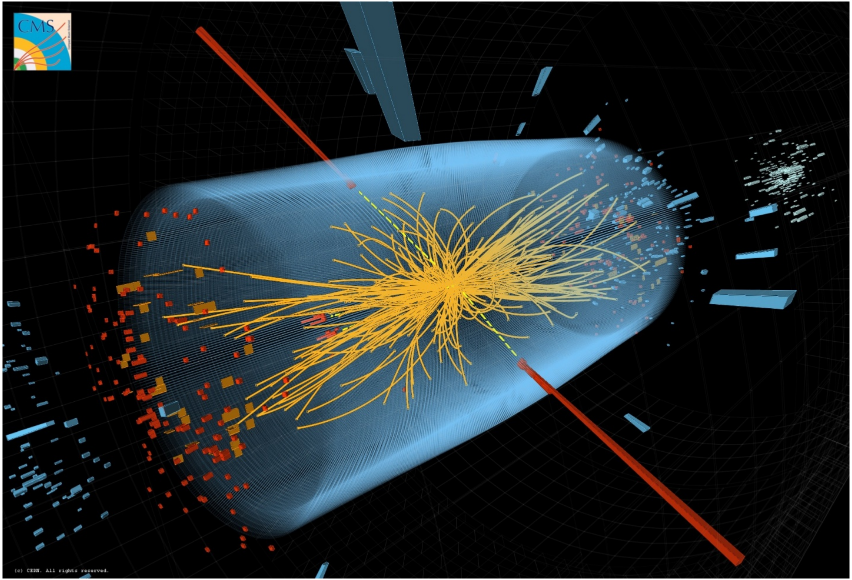
Event display of a $H \to 4e$ candidate;
$m_{4e} = 124.6$ GeV,
$m_{12} = 70.6$ GeV,
$m_{34} = 44.7$ GeV.



Event display of a $H \to 4\mu$ candidate with $m_{4\mu} = 124.6$ GeV. The masses of the lepton pairs are 89.7 GeV and 24.6 GeV.

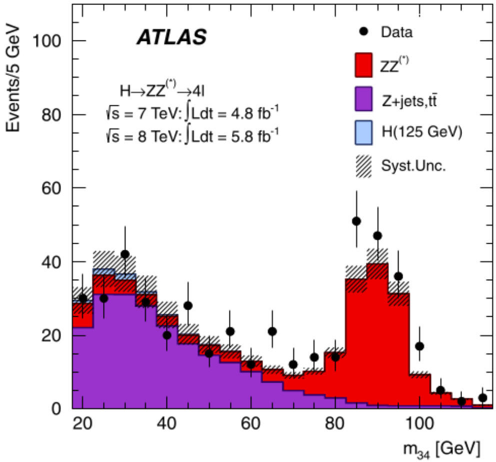


Real CMS proton-proton collision events in which 4 high energy muons (red lines) are observed. The event shows characteristics expected from the decay of a Higgs boson.



A typical candidate event including two high-energy photons whose energy (depicted by red towers) is measured in the CMS EM calorimeter. The yellow lines are the measured tracks of other particles produced in the collision. The pale blue volume shows the CMS crystal calorimeter barrel.

4-leptons channel



Main background processes:

- Z^*Z
- $Z+$jets
- $t\bar{t}$

Four different analysis sub-channels, $4e$, $2e2\mu$, $2\mu 2e$ and 4μ are defined.

Left: Invariant mass distribution of the sub-leading lepton pair (m_{34}) for a sample defined by the presence of a Z boson candidate and an additional same-flavor electron or muon pair, for the combination of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data in the entire phase-space of the analysis after the kinematic selections on the leptons.

The distribution of the four-lepton invariant mass, $m_{4\ell}$, for the selected candidates, compared to the background expectation in the 80–250 GeV mass range, for the combination of the $\sqrt{s} = 7$ and 8 TeV data.

The signal expectation for a SM Higgs with $m_H = 125$ GeV is also shown.

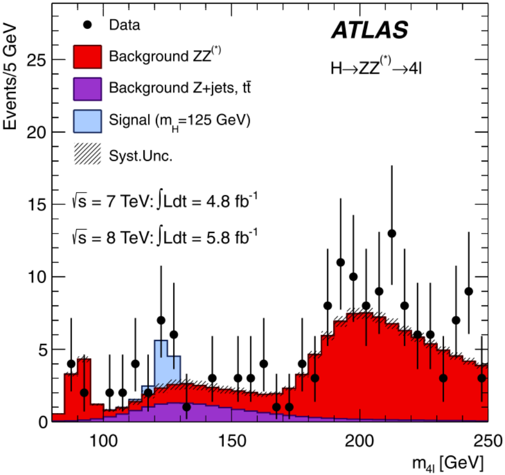


Figure 1: Physics Letters B Volume 716, Issue 1, 17 September 2012, P. 1-29

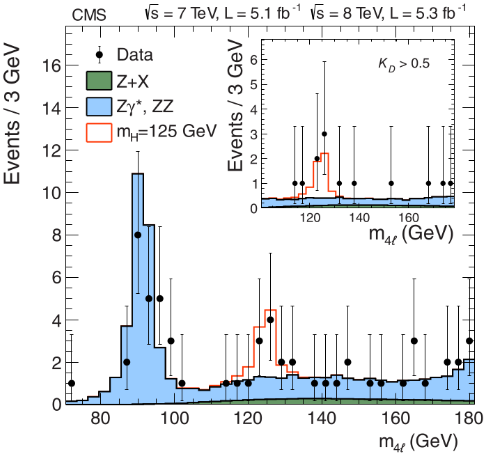


Figure 2: Physics Letters B Volume 716, Issue 1, 17 September 2012, P. 30-61

Distribution of the four-lepton invariant mass for the $ZZ \to 4\ell$ analysis in CMS.

The points represent the data, the filled histograms represent the background, and the open histogram shows the signal expectation for a Higgs boson of mass $m_H = 125$ GeV, added to the background expectation.

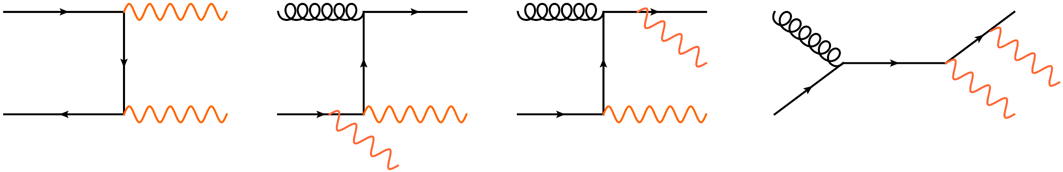
A kinematic discriminant is constructed based on the probability ratio of the signal and background hypotheses,
$k_D = \mathcal{P}_{\text{sig}}/(\mathcal{P}_{\text{sig}} + \mathcal{P}_{\text{bkg}})$.

The inset shows the $m_{4\ell}$ distribution after selection of events with $K_D > 0.5$.

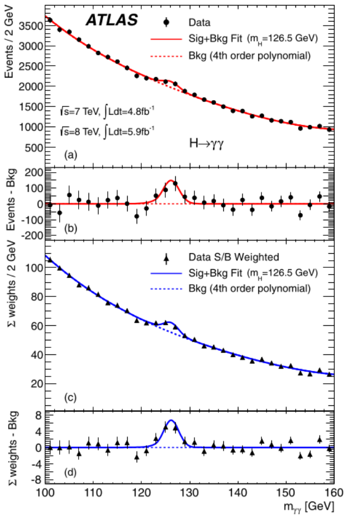
Diphoton channel

The search for the SM Higgs boson through the decay $H \to \gamma\gamma$ is performed in the mass range between 110 GeV and 150 GeV.

The dominant background is SM diphoton production:



Contributions also come from $\gamma + \mathrm{jet}$ and jet + jet production with one or two jets mis-identified as photons (γj and jj) and from the DrellYan process.



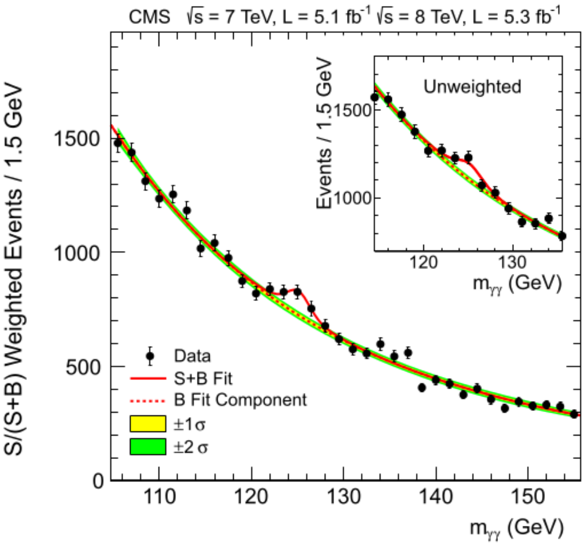
ATLAS: The distributions of the invariant mass of diphoton candidates after all selections for the combined $\sqrt{s} = 7$ TeV and 8 TeV data sample.

The inclusive sample is shown in (a) and a weighted version of the same sample in (c).

Event weights events are defined to be $\ln(1 + S/B)$, where S is 90% of the expected signal for $m_H = 126.5$ GeV, and B the integral a window containing S, of a background-only fit to the data.

The result of a fit including a signal component fixed to $m_H = 126.5$ GeV and a background component described by a 4^{th}-order Bernstein polynomial is superimposed.

The residuals of the data and weighted data with respect to the respective fitted background component are displayed in (b) and (d).



CMS: The diphoton invariant mass distribution with each event weighted by the $S/(S+B)$ value of its search category.

The lines represent the fitted background and signal.

The colored bands represent the ± 1 and ± 2 standard deviation uncertainties in the background estimate.

The inset shows the central part of the unweighted invariant mass distribution.

Missing transverse energy

At hadron colliders, the beams collide along the longitudinal direction and thus, due to energy-momentum conservation, the vectorial sum of all emerging particles' four-momenta should give zero contribution in the transverse plane.

Also, a significant and unknown proportion of the energy of the incoming hadrons in each event escapes down the beam-pipe.

Consequently if invisible particles are created in the final state, their net momentum can only be constrained in the plane transverse to the beam direction.

Defining the z-axis as the beam direction, this net momentum is equal to the missing transverse energy vector

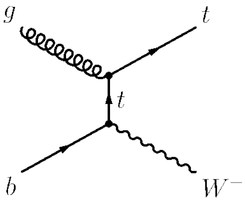
$$\mathbf{E}_T^{\text{miss}} = -\sum_i \mathbf{p}_T(i) \tag{1}$$

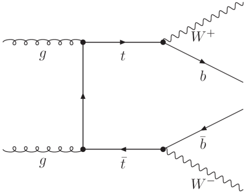
where the sum runs over the transverse momenta of all reconstructed, visible final state particles (jets, leptons).

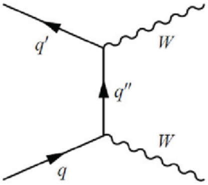
WW channel

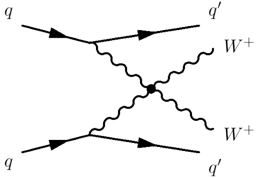
The signature for this channel is: two opposite-charge leptons with large transverse momentum and a large momentum imbalance in the event due to the escaping neutrinos.

The dominant backgrounds are non-resonant WW, $t\bar{T}$ and Wt production, all of which have real W pairs in the final state.



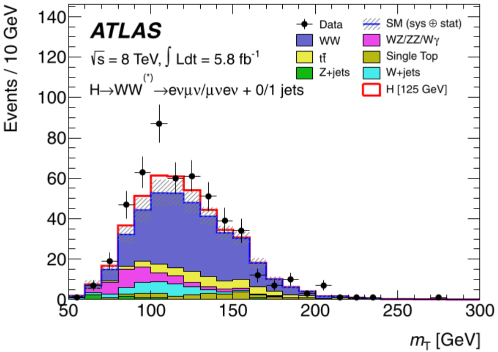






Other important back-grounds include

- DrellYan events ($pp \to Z/\gamma^* \to \ell\ell$) with $\mathbf{E}_T^{\text{miss}}$ that may arise from mismeasurement,
- W + jets events in which a jet produces an object reconstructed as the second lepton, and
- $W\gamma$ events in which the photon undergoes a conversion.



ATLAS: A transverse mass variable, m_T, is used to test for the presence of a signal for all jet multiplicities. This variable is defined as:

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - \left|\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\text{miss}}\right|^2} \quad (2)$$

with the transverse energy of the dilepton system being

$$E_T^{\ell\ell} = \sqrt{|\mathbf{p}_T^{\ell\ell}|^2 + |\mathbf{E}_T^{\text{miss}}|^2} \quad (3)$$

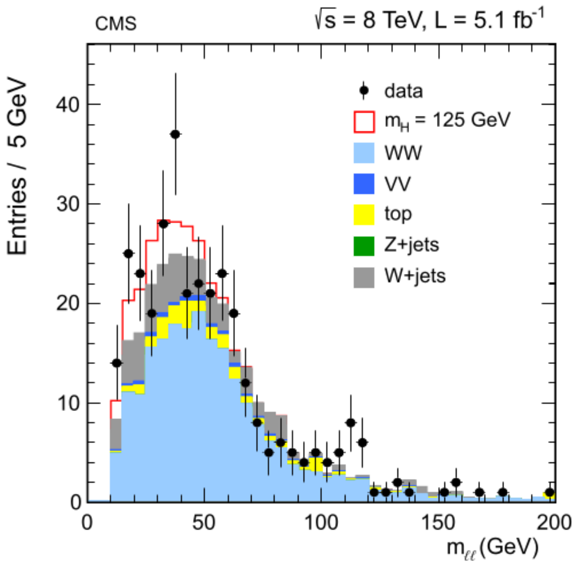
The expected signal for $m_H = 125$ GeV is shown stacked on top of the background prediction.

The hashed area indicates the total uncertainty on the background prediction

CMS: The decay mode $H \to WW$ is highly sensitive to a SM Higgs boson in the mass range around the WW threshold of $160~\mathrm{GeV}$.

Distribution of the dilepton invariant mass $m_{\ell\ell}$ in a category without jets of $p_T > 30~\mathrm{GeV}$ at $\sqrt{s} = 8~\mathrm{TeV}$.

The signal expected from a Higgs boson with a mass $m_H = 125~\mathrm{GeV}$ is shown added to the background.



Main systematic uncertainties

The main sources of systematic uncertainties are the following

1. Uncertainty on the integrated luminosity estimate
2. Electron and photon identification
3. Electron and photon energy scales
4. Muon reconstruction
5. Jet energy scale and missing transverse energy
6. Theoretical uncertainties affect mostly the signal predictions
7. Background estimate

Used as constraints in the statistical analysis to extract the best fir to the Higgs mass.

$\Rightarrow$ Animated plots of the Higgs discovery.

Hypothesis tests

One of the fundamental tasks in a statistical analysis is to test whether the predictions of a given model are in agreement with the observed data.

A hypothesis H means a statement for the probability to find the data $\mathbf{x}$. Equivalently, if $\mathbf{x}$ includes continuous variables, H specifies a probability density function or pdf.

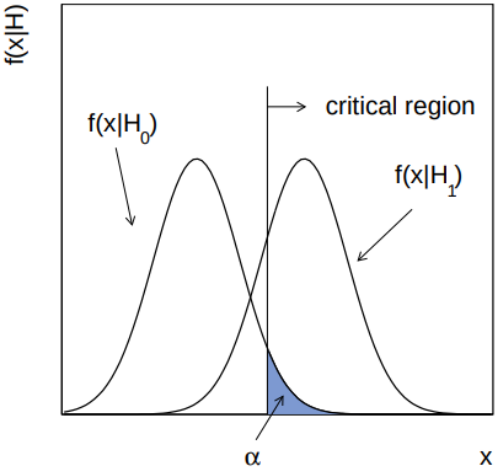
$P(\mathbf{x}|H)$ is used to denote the probability to find data $\mathbf{x}$ under assumption of the hypothesis H.

Consider a "null" hypothesis H_0 that we want to test and an "alternative" hypothesis H_1.

In frequentist statistics one defines a test of H_0 by specifying a *subset of the data space* called the critical region, w, such that the probability to observe the data there satisfies

$$P(\mathbf{x} \in w|H_0) \leq \alpha \tag{4}$$

Here α is a constant specified before carrying out the test, usually set by convention to a small value such as 5%.



The critical region w with a proability up to α defines the test: if the data are observed in w then the hypothesis H_0 is rejected.

In a significance test of a hypothesis H, one must specify what possible data values would constitute a level of incompatibility with H that is equal to, are greater than that between H and the observed data $\mathbf{x}_{\text{obs}}$.

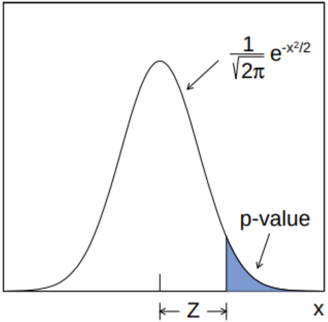
A p-value of H is calculated as the probability, under assumption of H, to find data in this region of equal or greater incompatibility.

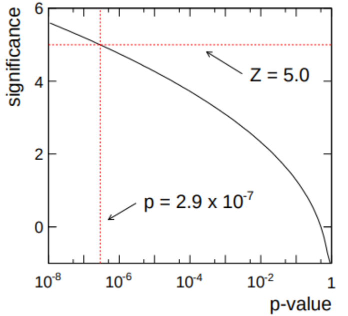
- In a frequentist test, we reject H_0 if the data are found in the critical region, or equivalently, if the p-value of H_0 is found less or equal to α (Ref. arXiv:1307.2487v1, 2013).

Often the p-value is translated into an equivalent quantity called the significance, Z, defined by

$$Z \equiv \Phi^{-1}(1 - p) \tag{5}$$

where Φ is the cumulative standard Gaussian distribution (zero mean, unit variance) and Φ^{-1} is its inverse function, also called the quantile of the standard Gaussian.





In HEP, a significance of $Z = 5$ is used as the threshold for claiming discovery of a new signal process.
This corresponds to a very low p-value of 2.9×10^{-7} for the *no-signal hypothesis*.

In HEP searches, the hypotheses we want to test are

- H_0 : only background processes exist, versus the alternative
- H_1: both signal and background exist.

If the signal does exist, then we will find both signal and background events.

We typically refer to the hypothesis H_0 as the background-only model, or simply b and the alternative H_1 as the signal-plus-background model, $s + b$.

$\Rightarrow$ Rejecting H_0 means in effect discovering a new phenomenon.

Limits in cases of low sensitivity

Suppose a search characterized by parameter μ being proportional to the cross section for the signal process whose existence is not yet established.

Here one often wants to test a hypothetical value relative to the alternative hypothesis H_0 that the signal does not exist, i.e. $\mu = 0$ (b only), to hypothesis H_1 with signal, .e. $\mu > 1$ ($b + s$).

The CL$_s$ method is designed for cases when the distributions of a test statistic Q under the two hypotheses blues$s + b$ and b are very close together. That is, the threshold for rejecting a model is altered in a way that prevents one from rejecting a model in the limit that one has very little sensitivity, but reverts to the usual frequentist procedure when the sensitivity is high.

Literally, for a test statistic Q given by the likelihood ratio

$$Q = -2 \ln \frac{L(\mu = 1)}{L(\mu = 0)} \tag{6}$$

this is defined as

$$\mathsf{CL}_s \equiv \frac{P(Q \geq Q_{\mathsf{obs}} | s + b)}{P(Q \geq Q_{\mathsf{obs}} | b)} = \frac{p_{s+b}}{1 - p_b} \tag{7}$$

⇒ The $s + b$ model is *rejected* if one finds CL$_s \leq \alpha$.

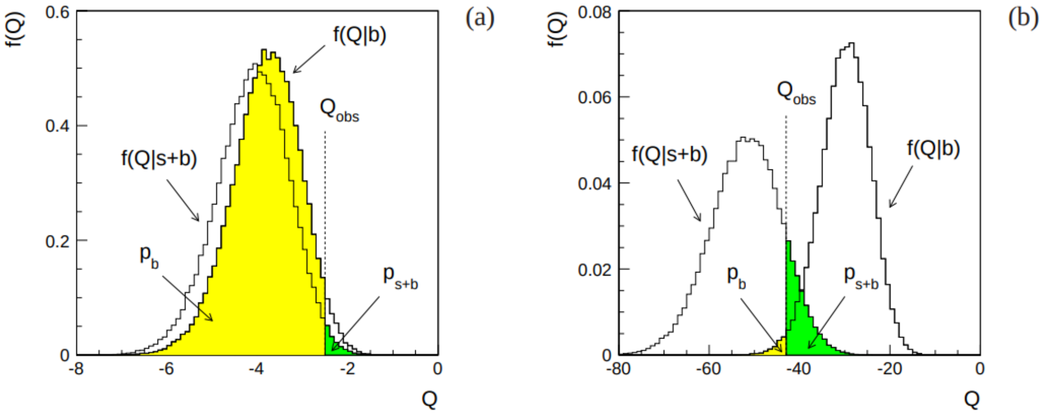


Figure 3: Illustration of the CL_s method: (a) Distributions of the statistic Q indicating low sensitivity to the hypothesized signal model; (b) illustration of the ingredients for the CLs limit.

Now, back to the LHC results...

The production of a Higgs-like signal is characterized by two parameters of interest:

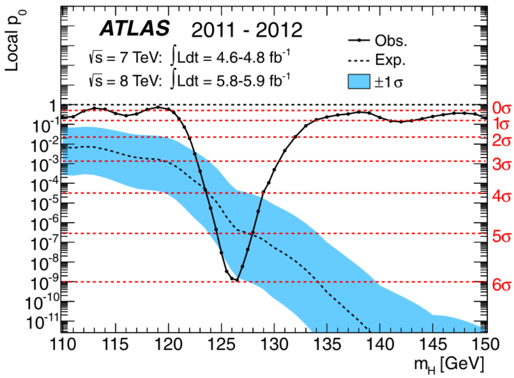
1. the strength parameter which is defined here as the signal cross section divided by the one predicted by the Standard Model, $\mu = \sigma/\sigma_{\mathsf{SM}}$,
2. the mass of the resonance, labeled m_H.

The procedure is to carry out tests of μ for a set of fixed masses within a given range, and the results are then interpolated, here $m_H = 110 - 150 \text{ GeV}$.

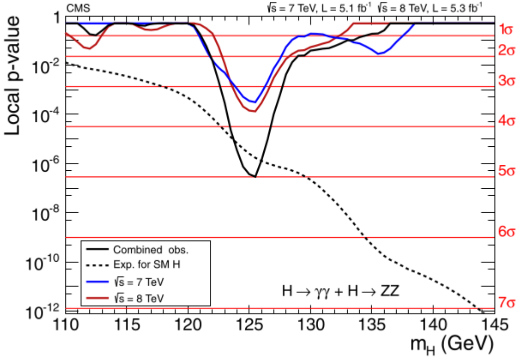
One obtains from this 2 important outputs, both as a function of m_H:

1. p-values for the test of $\mu = 0$, and
2. upper limits for μ at confidence level of $1 - \alpha$, i.e. the highest value of μ that we *do not reject*

Statistical results



The observed (solid) local p_0 as a function of m_H in the low mass range. The dashed curve shows the expected local p_0 under the hypothesis of a SM Higgs boson signal at that mass with its $\pm 1\sigma$ uncertainty band. The horizontal dashed lines indicate the p-values corresponding to significances of 1 to 6 σ.



The observed local p-value for decay modes with high mass-resolution channels, $\gamma\gamma$ and ZZ, as a function of the SM Higgs boson mass. The dashed line shows the expected local p-values for a SM Higgs boson with a mass m_H.

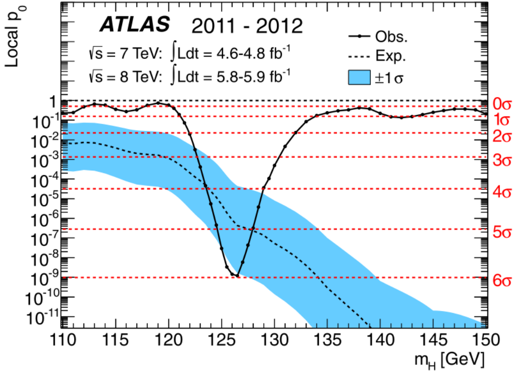
Statistical interpretation

The p-value of the background-only hypothesis p_0 is shown versus m_H.

On the right-hand side of the plot one can see the value translated into the significance Z.

The lowest p-value is found at $m_H = 126.5$ GeV and corresponds to $Z \simeq 6.0$.

The dotted line $(\cdots\cdots)$ gives the median value of Z under the hypothesis that the Higgs boson is present at the rate predicted by the Standard Model, i.e. $\mu = 1$.

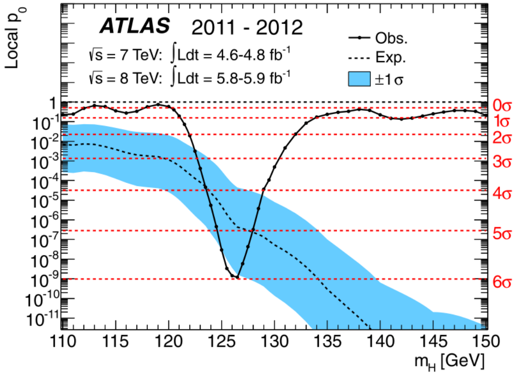


That is, if one were to generate a data set assuming an SM Higgs boson with a mass of 126.5 GeV, then this will lead to a certain significance Z for a test of $\mu = 0$.

If one were to generate an ensemble of such experiments then the median of the resulting distribution of Z values, usually referred to as the expected significance, is taken as a measure of the "sensitivity of the measurement".

For $m_H = 126.5$ GeV the expected significance is $Z = 4.9$, as can be seen from the dotted line.

The blue band corresponds to the 68% inter-quantile range, i.e., the lower and upper edges of the band referred to as the $\pm 1\sigma$ uncertainty band.



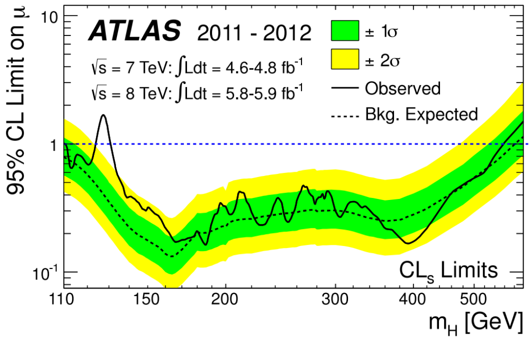
The band quantifies how much variation of the result to expect as a result of statistical fluctuations if the nominal signal model is correct.

If the $\mu = 1$ hypothesis is in fact correct, then the signal rate **observed** by ATLAS fluctuated above the **expected** median value by a bit more than one standard deviation.

CL_s upper limits on the production cross section for the Higgs boson as a function of its mass.

The solid curve shows the observed upper limit using the CL_s procedure.

For each mass the distribution of upper limits was found under assumption of background only, $\mu = 0$, and the dotted curve shows the median value.



The green and yellow bands show the ranges that correspond to $\pm 1\sigma$ and $\pm 2\sigma$ interval around the fitted value.

$\twoheadrightarrow$ For almost all mass values the observed limit is close to the expectation under assumption of $\mu = 0$.

The exception is the mass region around 126 GeV, where the upper limit is significantly higher, corresponding to the discovered signal.

Combined m_H measurement

The combined measurement of the Higgs boson mass is performed in the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ channels using the LHC Run 1 data sets of the ATLAS and CMS experiments.

The measurement of m_H, along with its uncertainty, is based on the maximization of profile likelihood ratios

$$\Lambda(\boldsymbol{\alpha}) = \frac{L(\boldsymbol{\alpha}, \hat{\hat{\boldsymbol{\theta}}}(\boldsymbol{\alpha}))}{L(\hat{\boldsymbol{\alpha}}, \hat{\boldsymbol{\theta}})} \tag{8}$$

in the asymptotic regime, where

- L represents the likelihood function,
- $\boldsymbol{\alpha}$ the parameters of interest and $\boldsymbol{\theta}$ the set of nuisance parameters
- $\hat{\boldsymbol{\alpha}}$ and $\hat{\boldsymbol{\theta}}$ terms denote the unconditional maximum likelihood estimates of the best-fit values for the parameters
- $\hat{\hat{\boldsymbol{\theta}}}(\boldsymbol{\alpha})$ is the conditional maximum likelihood estimate for given parameter values $\boldsymbol{\alpha}$

The likelihood functions L are constructed using signal and background probability density functions (PDFs) that depend on the discriminating variables: for the $\gamma\gamma$ channel, the diphoton mass $m_{\gamma\gamma}$ and, for the 4ℓ channel, the four-lepton mass $m_{4\ell}$.

Scans of twice the negative log-likelihood ratio $-2\ln\lambda(m_H)$ as functions of the Higgs boson mass m_H for the ATLAS and CMS combination of the $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$, and combined (black) channels.

The dashed curves show the results accounting for statistical uncertainties only, with all nuisance parameters associated with systematic uncertainties fixed to their best-fit values.

The 1 and 2 standard deviation limits are indicated by the intersections of the horizontal lines at 1 and 4, respectively, with the log-likelihood scan curves.

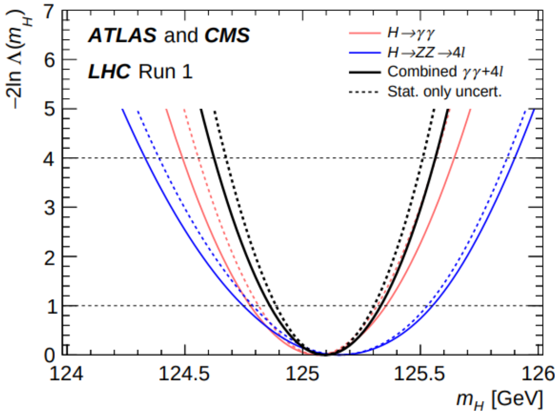


Figure 4: Adapted from arXiv:1503.07589v1, 2015.

$$\boxed{m_H = 125.09 \pm 0.24 \text{ GeV} = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.) GeV}} \quad (9)$$

ATLAS:

improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

CMS:

signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of 125.3 ± 0.4(stat.) ± 0.5(syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

Higgs-dependence Day - July 4, 2012

Nobel Price

The Nobel Prize in Physics 2013

Photo: A. Mahmoud

François Englert

Prize share: 1/2

Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Combined results with data at $\sqrt{s} = 7,\ 8,\ 13\ \mathrm{TeV}$

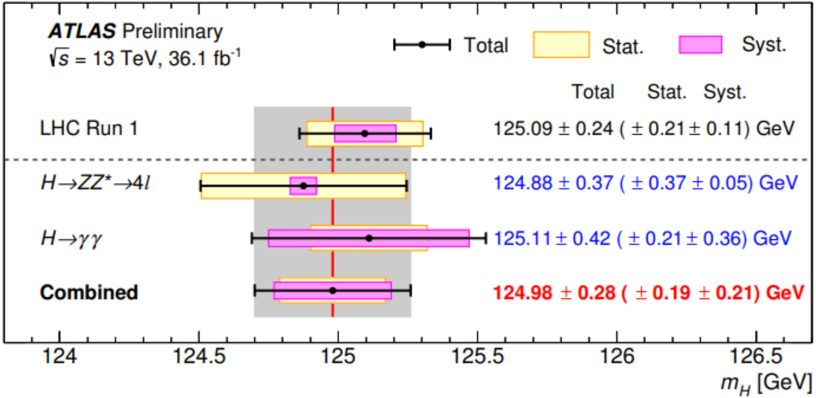


Figure 6: Ref. ATLAS-CONF-2017-046, 2017.

Summary of the Higgs boson mass measurements from the individual and combined analyses performed with data at $\sqrt{s} = 13\ \mathrm{TeV}$, compared to the combined Run 1 measurement by ATLAS and CMS at $\sqrt{s} = 7,\ 8\ \mathrm{TeV}$.

Synopsis

Since the discovery of the W and Z bosons in the mid 1980s, the search for the Higgs boson has been the highest priority in particle physics. Its discovery in 2012 at LHC with a mass

$$m_H \simeq 125 \text{ GeV} \tag{10}$$

Following the discovery of the Higgs boson, the observation of the SM-like Higgs boson in fermion final states is equally important.

Also, studies of its properties are necessary to proof that it is the SM Higgs boson and possibly provide clues to physics beyond the Standard Model.