Twenty Years of Searching for the Higgs Boson: Exclusion at LEP, Discovery at LHC

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Abstract. The 40 years old Standard Model, the theory of particle physics, seems to describe all experimental data very well. All of its elementary particles were identified and studied apart from the Higgs boson until 2012. For decades many experiments were built and operated searching for it, and finally, the two main experiments of the Large Hadron Collider at CERN, CMS and ATLAS, in 2012 observed a new particle with properties close to those predicted for the Higgs boson. In this paper we outline the search story: the exclusion of the Higgs boson at LEP, the Large Electron Positron collider, and its observation at LHC.

1. Introduction: the Standard Model

The Standard Model, the general theory of particle physics was established more than 40 years ago. It describes our world as consisting of two kinds of elementary particles, fermions and bosons, differing by their spin, intrinsic angular momentum: fermions have half-integer, bosons have integer spins measured in units of $\hbar$, the reduced Planck constant. The elementary fermions have three families, each consisting of one pair of quarks and one pair of leptons (Table 1). Every fermion has an antiparticle of the opposite charge. The leptons can propagate freely, but the quarks are confined in hadrons: they can only exist in bound states of three quarks, baryons (like the proton and neutron) or those of a quark and an antiquark, mesons (like the pion). Three antiquarks make antibaryons like the antiproton.

In the Standard Model the three basic particle interactions, the strong interaction holding the quarks in the nucleons and the nucleons in the atomic nucleus, the weak interaction, responsible for the decay of the heavier basic fermions, and the well known electromagnetic interaction, are all derived from local gauge symmetries. A gauge symmetry is a freedom to define the coordinate system measuring the strength of an interaction, the best known example of which is the freedom to choose the potential zero of an electric field. A local symmetry is its modified form when the gauge is changing in space-time according to a known function. The three basic interactions are mediated by elementary bosons: the strong nuclear force by 8 gluons, the weak interactions by the three heavy weak bosons and the electromagnetism by the photon. In order to cancel uncomfortable terms from equations the theory also needs the existence of an additional scalar boson, a particle with all its quantum numbers like charges and spin zero.

Local gauge symmetries give correct answers to important questions except the mass of elementary particles: one has to violate them in order to get non-zero masses. This spontaneous

	Family 1	Family 2	Family 3	charge	T_3
Leptons	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	0 -1	$+\frac{1}{2}$ $-\frac{1}{2}$
Quarks	$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{2}$ $-\frac{1}{2}$

Table 1. Leptons and quarks, the three families of basic fermions. T_3 is the third component of the weak isospin, the rest of the notation is explained in the text step by step.

symmetry breaking (SSB) mechanism was introduced in several steps to particle physics and it is now an integral part of the Standard Model. It is called, somewhat unjustified, also the Higgs mechanism, although it is the product of several people, so it could also be called *Brout–Englert–Higgs–Guralnik–Hagen–Kibble* mechanism.[1–5] These days we try to call it BEH mechanism by the initials of those who have first published it. As the scalar boson was first introduced by Peter Higgs, it is justly called Higgs boson.

The spontaneous symmetry breaking mechanism consists of adding to the electroweak vacuum a potential which breaks its perfect symmetry. The form of this potential is

$$V = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \tag{1}$$

where Φ is a complex doublet field of four components and $\lambda > 0$ is a real constant. If $\mu^2 > 0$ then it is a scalar field with a non-zero mass μ and a potential minimum at $\Phi = 0$. However, if $\mu^2 < 0$ then it has a non-zero minimum

$$\Phi^\dagger \Phi = \tfrac{1}{2}(\Phi_1^2 + \Phi_2^2 + \Phi_3^2 + \Phi_4^2) = -\frac{\mu^2}{2\lambda}. \tag{2}$$

Φ can be chosen so that it had just one real component and then expanded around its minimum, *vacuum expectation value* $v = \sqrt{-\frac{\mu^2}{\lambda}}$ as

$$\Phi(x) = \sqrt{\tfrac{1}{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \tag{3}$$

The Φ field is imposed onto the vacuum of the $U(1)_Y \otimes SU(2)_L$ combined local gauge symmetries, breaking them. Here

$$Y = 2(Q - T^3) \tag{4}$$

the hypercharge of the fermion (where Q is the electric charge and T^3 is the third component of the weak isospin, see Table 1), and $SU(2)_L$ acts on left-polarized fermion doublets. As the photon has zero mass, from the neutral part of the electroweak Lagrangian we separate a good $U(1)_Q$ using relation (4) between electric charge Q and hypercharge Y, and the rest gives a correct weak interaction with three massive gauge bosons, $W^\pm$ and Z. As a result of this manipulation, 3 components of the Φ field become the longitudinal polarizations (masses) of the 3 $SU(2)$ gauge bosons and the fourth component makes the scalar Higgs boson. The charged currents of the weak interaction, mediated by $W^\pm$ are pure $SU(2)_L$ whereas Z is the result of the unification, thus they have different masses and Z mediates a right-handed neutral current as well.
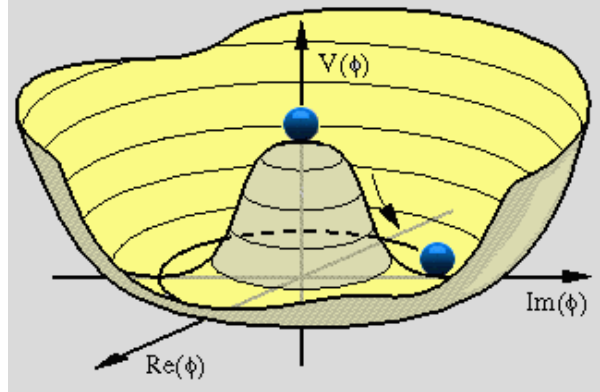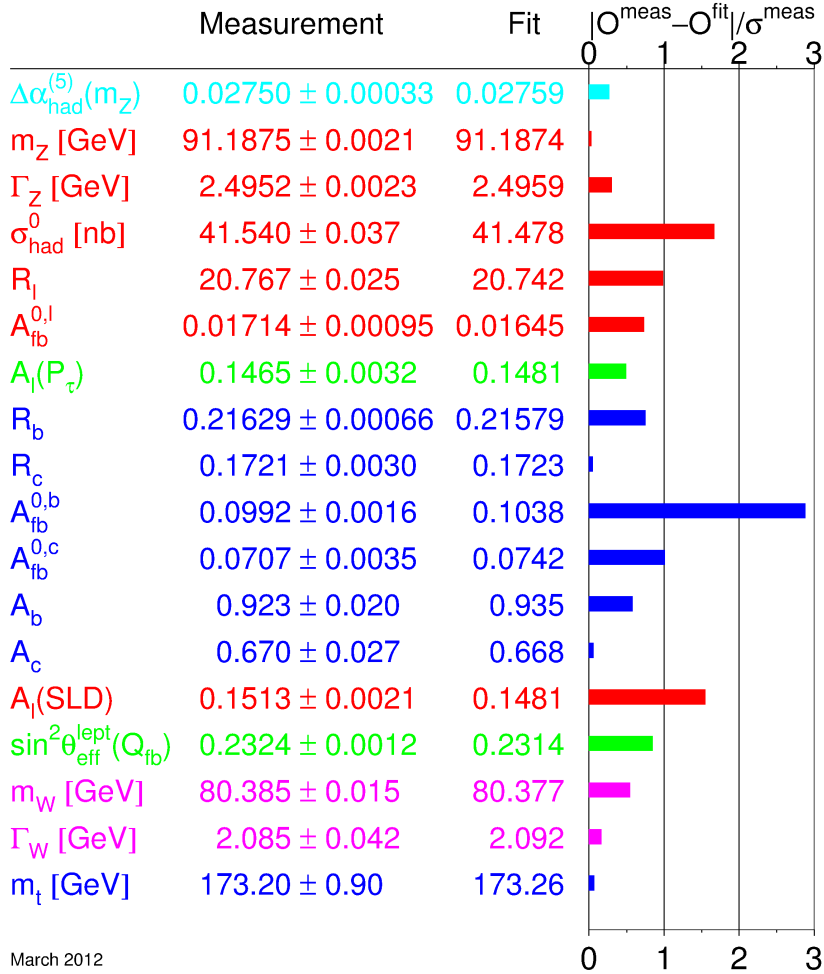
Figure 1. Spontaneous symmetry breaking: the BEH potential. The axial symmetry of the potential is not violated by putting a ball on the top at $\Phi = 0$, but it will be spontaneously broken when the ball rolls down in the valley. However, the coordinate system can always be chosen so that the ball were at point $Im(\Phi) = 0$.

Spontaneous symmetry breaking is well illustrated by a Mexican hat (Fig. 1). Its axial symmetry is not violated by putting a ball on its top, however, the ball will eventually go down and break the original symmetry. SSB makes it possible to introduce masses in the theoretical equations: masses for the heavy weak bosons, W^+, W^- and Z^0 mediating the weak interaction and also masses for the basic fermions, the quarks and leptons. There is a substantial difference, however: whereas the masses of the weak bosons appear as a result of SSB, and so they are predicted by the Standard Model, the fermion mass terms have to be added ad hoc to the Standard Model Lagrangian as a triple interaction among the left-polarized fermion doublet, the (3) BEH doublet and the right-polarized fermion singlet field with arbitrary coupling constants giving the fermion masses. The BEH field introduces 2 free parameters in the Standard Model; as the vacuum expectation value can be determined from the Fermi coupling constant ($v \sim 246$ GeV), the only adjustable parameters left in the electroweak theory are the $U(1)$ and $SU(2)$ coupling constants and the masses of the fermions and of the Higgs boson.

Note that the masses of our macroscopic world are mostly due to the energy content of the proton and neutron and not due to the BEH mechanism.

Since almost 40 years, more and more precise new data were acquired at the particle accelerators and all seem to agree very well with the predictions of the Standard Model. Hundreds of experiments are summarized in the few parameters of Fig. 2 according to the LEP Electroweak Working Group.[6] It shows the 2012 situation of the analysis of electroweak data: all experimental data and theoretical estimates agree within the statistical boundaries. The only parameter which deviates at more than 2 uncertainties is the forward-backward asymmetry of the decay of the Z boson to two b quarks.

The Higgs boson of the Standard Model is the only scalar particle: all of its quantum numbers are zero, its only property is mass. Fitting experimental data predicts that the Higgs mass should be around 100 GeV (between 80 and 160 GeV within 95% confidence). All constituents of the Standard Model were identified and studied experimentally before the launch of the LHC, apart from the Higgs boson, that is how it became the most wanted particle. As Peter Higgs himself told[7] "It was in 1972 ... that my life as a boson really began".

	Measurement	Fit	$|O^{meas}-O^{fit}|/\sigma^{meas}$
			0 1 2 3
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^0 [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
$A_l(SLD)$	0.1513 ± 0.0021	0.1481	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.385 ± 0.015	80.377	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.20 ± 0.90	173.26	

March 2012

Figure 2. Various parameters of the Standard Model:[6] average measured values (2nd column) with uncertainties (3rd column), the predictions or fits by the Standard Model (4th column) and a bar plot showing the differences between theory and experiment divided by the experimental uncertainties. The agreement is purely statistical as the difference is in only one case more than 2 uncertainties.

2. Analysis Concepts of Particle Physicists

The statistical methods[1] used by particle physicists are as different from the *official* mathematical statistics as mechanical engineering from the Lagrangian or Hamiltonian formulation of theoretical mechanics. At the same time statistics is extremely important for data analysis in particle physics: every few years international workshops are organized by particle physicists working at the Large Hadron Collider to exchange ideas on statistical methods, the last one having been in 2011.[9] In the Appendix of that volume *Eilam Gross* defines the aim of his paper *LHC Statistics for Pedestrians*: *"A pedestrian's guide ... to help the confused physicist to understand the jargon and methods used by HEP phystatisticians. ... A phystatistician is a physicist who knows his way in statistics and knows how Kendall's advanced theory of statistics book looks like.*

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[1] This section follows the line of ref.[8]

Every high-energy collaboration has phystatistician experts and they all have quite different ideas how to analyze data. In order to avoid confusion, the large LHC collaborations have Statistics Committees which publish home pages of recommendations how to do things. The Statistics Committees of both CMS and ATLAS have several members who published text books on statistics for physicists and ATLAS and CMS have a joint such committee as well.

As in high energy physics the primary experimental data are basically event counts, the basic concepts are Poisson-like. The data follow the Poisson distribution (n_i events in bin i): $\mathcal{P}(n_i|\mu_i) = \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}$ and the result is usually expressed in terms of the Poisson likelihood: $\mathcal{L} = \Pi_i \mathcal{P}(n_i|\mu_i)$. The expected number of events is $\tilde{\mu}_i = \sum_j L\sigma_j \epsilon_{ji}$, where L is the integral luminosity collected, σ_j is the cross section of source j and ϵ_{ji} is the efficiency (determined by Monte Carlo simulation) of source j in bin i.

Luminosity is the rate of collecting data for colliders, similar to the flux of fixed-target experiments. It is defined as $L = fn\frac{N_1 N_2}{A}$ where f is the circulation frequency of the colliding beams; n is the number of particle bunches in the ring; N_1, N_2 are the numbers of particles in the two kinds of bunches; A is the spatial overlap of the colliding bunches. The total number of collisions is characterized by the integrated luminosity: $\int_{t_1}^{t_2} L dt$ which is usually measured in units of inverse cross-section, at LHC in [pb^{-1}, fb^{-1}]. The expected rate of a reaction with cross section σ at ϵ detection efficiency is $R = \epsilon\sigma L$.

According to the general convention in accelerator experiments a given new phenomenon is excluded if we can show it not appearing at a $\geq 95\%$ confidence level and observed if it exceeds $> 5\sigma$ above background where now, for a change, σ is the experimental uncertainty according to the best honest guess of the experimentalist.

That σ uncertainty has a *statistical component* from the number of observed events and *systematic* ones from various sources, like Monte Carlo statistics and inputs, experimental calibration factors, detection efficiencies, etc, with the common name *nuisance parameters*. To get a rough estimation of the total error the systematic uncertainties could be added quadratically to the statistical one: $\sigma = \sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2}$, but in practice we derive the final uncertainty via marginalizing (integrating out)[10] the nuisance parameters Θ in likelihood $\mathcal{L}$ using the related probability distributions $\mathcal{W}$: $\mathcal{L}(P;x) = \mathcal{W}(x|P) = \int \mathcal{W}(x|P,\Theta)\mathcal{W}(\Theta|P)d\Theta$.

Another important feature of high-energy data analysis is the *blind analysis*:[11] "A blind analysis is a measurement which is performed without looking at the answer. Blind analyses are the optimal way to reduce or eliminate experimenter's bias, the unintended biasing of a result in a particular direction." It came from medical research and the idea is to optimize, prove and publish your analysis technique using simulations and earlier data only before touching new data in the critical region. For instance, in Spring and early Summer, the 2012 CMS data were blinded in the invariant mass region $110 < M_H < 140$ GeV (where M_H is the simulated Higgs mass) because of the 3σ excess observed in 2011. The same procedure was used again in Autumn 2012. The methods had to be fixed and approved by the collaboration before simultaneous *unblinding* for all analysis channels.

3. Search for the Higgs boson

What we usually try to observe is a resonance. For a particle with lifetime $\tau = \Gamma^{-1}$ and decay rate Γ the event rate against the invariant mass of the decay products is $|\chi(E)|^2 = \frac{1}{(E-M)^2+\Gamma^2/4}$, i.e. a Lorentz curve (Breit-Wigner resonance). It shows a peak at the M invariant mass of the decaying system with a full width at half maximum Γ. The discovery of a new particle can be claimed if we see a resonance at the same invariant mass of the particle in all expected decay channels, by all related experiments. Many hopeful new observations were disproved as statistical fluctuations by other experiments, and a few stayed unproven as not confirmed.

The search involves several consecutive steps.

- Compose a complete *Standard Model background* using Monte Carlo simulation taking into account all types of possible events normalized to their cross-sections.
- Compose *Higgs signals*, simulations of all possible production and decay processes with all possible Higgs-boson masses.
- Put all these through the *detector simulation* to get events analogous to the expected measured ones.
- *Optimize the event selection* via reducing the B background and enhancing the S signal via maximizing e.g. $N_S/\sqrt{N_B}$ or[12] $2 \cdot (\sqrt{N_S + N_B} - \sqrt{N_B})$.
- *Check the background*, i.e. the description of data by the simulation for the given luminosity: the simulation should reproduce the observed background distributions in all details. For instance, you can check the background of the decay of a neutral particle to charged leptons by selecting lepton pairs of identical charges.
- *Check the signal:* does it agree with the expectation by the theoretical model?

Once you are happy with the simulations and the event selection, you must chose a test statistic. That could be any kind of probability variable characteristic of the given phenomenon: probabilities for having background only, for having signal or combinations. One of the favorite is the Q likelihood ratio of signal + background over background: $Q = \mathcal{L}_{s+b}/\mathcal{L}_b$. As you see, although our basic approach is definitely frequentist there is a certain Bayesian influence as well. What most frequently plotted is

$-2\ln Q(m_H) = 2\sum_{k=1}^{N_{\mathrm{ch}}} \left[s_k(m_H) - \sum_{j=1}^{n_k} \ln \left(1 + \frac{s_k(m_H)S_k(x_{jk};m_H)}{b_k B_k(x_{jk})} \right) \right]$

Here the variables are the following:

- n_k: events observed in channel k, $k = 1 \ldots N_{\mathrm{ch}}$.
- $s_k(m_H)$ and b_k: signal and background events in channel k for Higgs mass m_H.
- $S_k(x_{jk};m_H)$ and $B_k(x_{jk})$: probability distributions for events for Higgs mass m_H at test point x_{jk}.
- x_{jk}: position of event j of channel k on the plane of its reconstructed Higgs mass and cumulative testing variable constructed of various special features of the event like b-tagging, signal likelihood, neural network output, etc.

Several other testing variables can be constructed on the same basis, the most frequently used ones are probabilities of NOT having the expected signal on the basis of the expected background and the collected data:

- CL_b, the signal confidence level assuming background only, i.e. the complete absence of the signal, or
- The so-called $p-value$: the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true. Translated to our language that means the probability that random fluctuation of the measured background could give the observed excess (if any).

4. Exclusion at LEP
Although the experiments of the Large Electron Positron (LEP) collider (Fig. 3) saw no earthshaking discoveries, no real deviation from the Standard Model, LEP provided an incredible amount of very precise measurements, some of which are presented in Fig. 2. In its last two years of working, LEP was mostly devoted to the search for the Higgs boson, collecting more luminosity at higher energies than in the previous 10 years together.
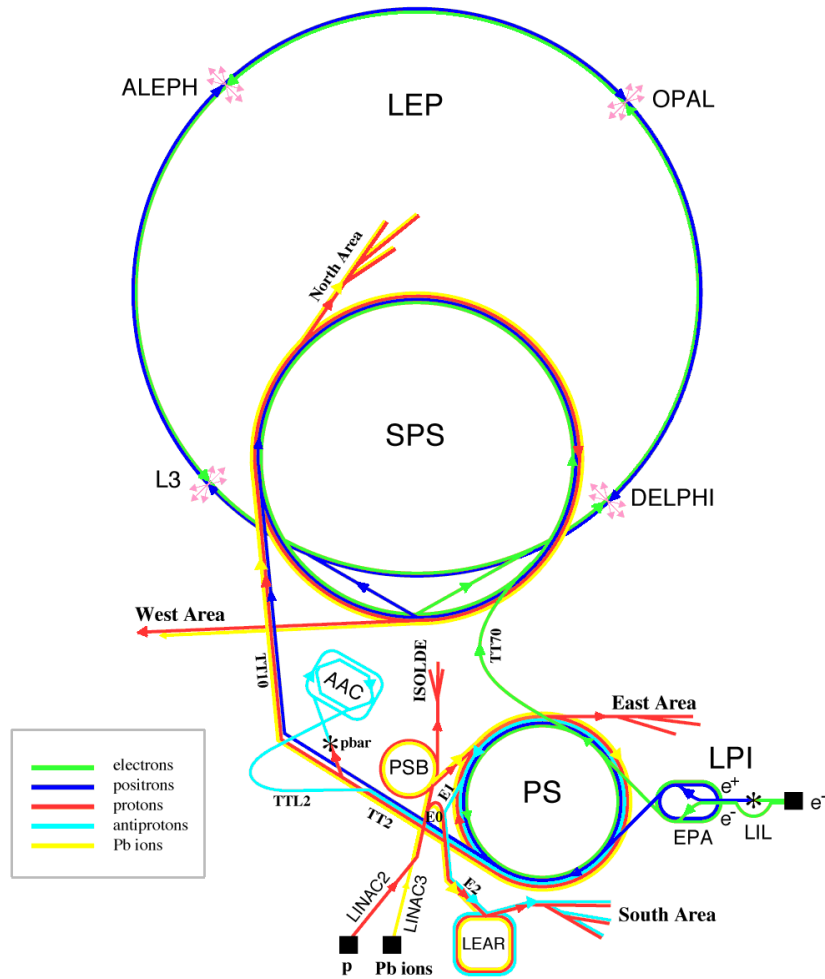
Figure 3. The accelerator complex of CERN in the LEP era

At LEP the dominant formation process is *Higgs-strahlung* e⁻e⁺→ZH (the name comes from the funny *English* word Bremsstrahlung[2]) and the dominant Higgs decay is to 2 b-quarks. The various channels are different only due to the various decay processes of the accompanying Z boson.

LEP had 4 large experiments (Fig. 3) in the 4 interaction points of the electron-positron collider, ALEPH, DELPHI, L3 and OPAL (the present author was working in OPAL). The structure of all contemporary high-energy detectors are very similar, consisting of onion-like layers. A sensitive pixel detector right around the beam pipe, a tracking system of multiwire chambers or semiconductor detectors of minimal weight material following the tracks of charged particles in the magnetic field of the detector, then an electromagnetic calorimeter, something heavy absorbing all electrons and photons, outside of that an even heavier hadron calorimeter, absorbing the pions, protons, neutrons, etc., and finally, muon chambers, identifying the path of energetic muons leaving the system. All detectors have huge magnets encompassing as much as possible of the detector parts. Figure 5 shows a Higgs-boson-like event detected by ALEPH in the 4-jet channel.

Statistics played a rough joke at LEP: one of the experiments, ALEPH, saw in one of the

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[2] Other languages use the simple mirror translation of the German word: *braking radiation*
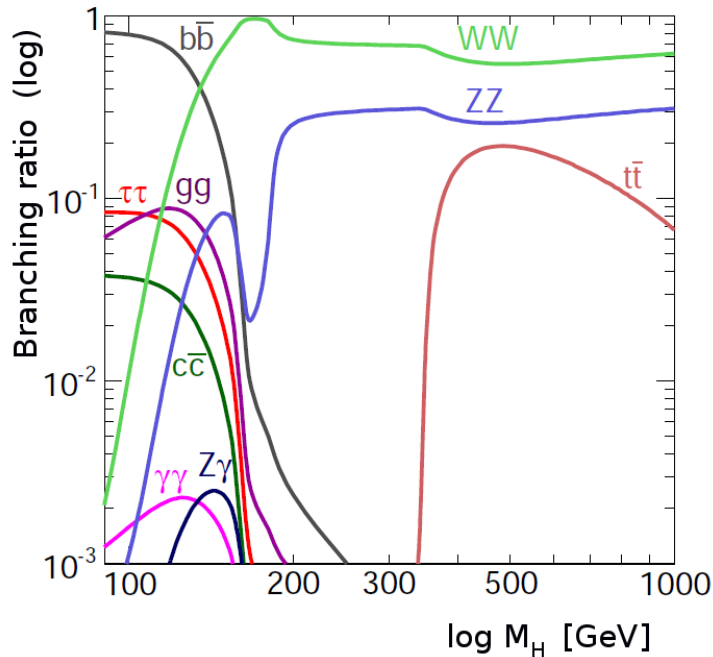
Figure 4. The various decay channels of the Higgs boson according to the Standard Model. Below 120 GeV the H→ b$\bar{\text{b}}$ decay channel dominates.

possible Higgs decay channels a very significant signal corresponding to a Higgs boson of a mass of 115 GeV/c^2, while the rest of LEP have not seen anything[13] (Fig. 6). ALEPH saw the excess in 4-jet events only, in those events where the Higgs boson decays to a pair of b quarks and the accompanying Z boson also decays to a quark pair (Fig. 5). The b quark is identified by its long lifetime leading to a secondary decay vertex in the event. Another strange thing was that the Higgs signal seen by ALEPH by far exceeded the expectations of the Standard Model. Also, the observed Higgs mass was critical as it coincided with the average kinematic limit of LEP: in 2000 the average collision energy of LEP was about 206 GeV and the observed resonance was found at 115 GeV/c^2, the difference is very close to the mass of the Z boson, 91 GeV/c^2.

A quite interesting feature of data analysis was the plotting of *spaghetti diagrams*. Those are signal weight distributions of each selected event as a function of the assumed Higgs mass. Fig. 7 shows the weight distributions of 17 selected Higgs-like candidate events observed by the 4 LEP experiments.[13] The ALEPH events crowd around 115 GeV/c^2 whereas for the other 3 experiments there are less of them with a rather random mass distribution. This caused quite an excitement at LEP: many physicists signed the petition to the Director General of CERN to extend the life of LEP by another year, but that was refused: the simulated projections were not very promising for a discovery of the SM Higgs boson (the effect seen by ALEPH only was far too large, much higher than the prediction of the Standard Model), and the contractors for building LHC were already prepared to start.

5. Search and observation at LHC
Figure 8 shows the various formation processes of the SM Higgs boson in p-p collisions at LHC. The dominant reaction is gluon fusion and vector boson fusion is also significant.

Just like LEP had, the Large Hadron Collider has also 4 interaction points (Fig. 9) with a major experiment (and sometimes a smaller one as well) in each. The two largest ones,
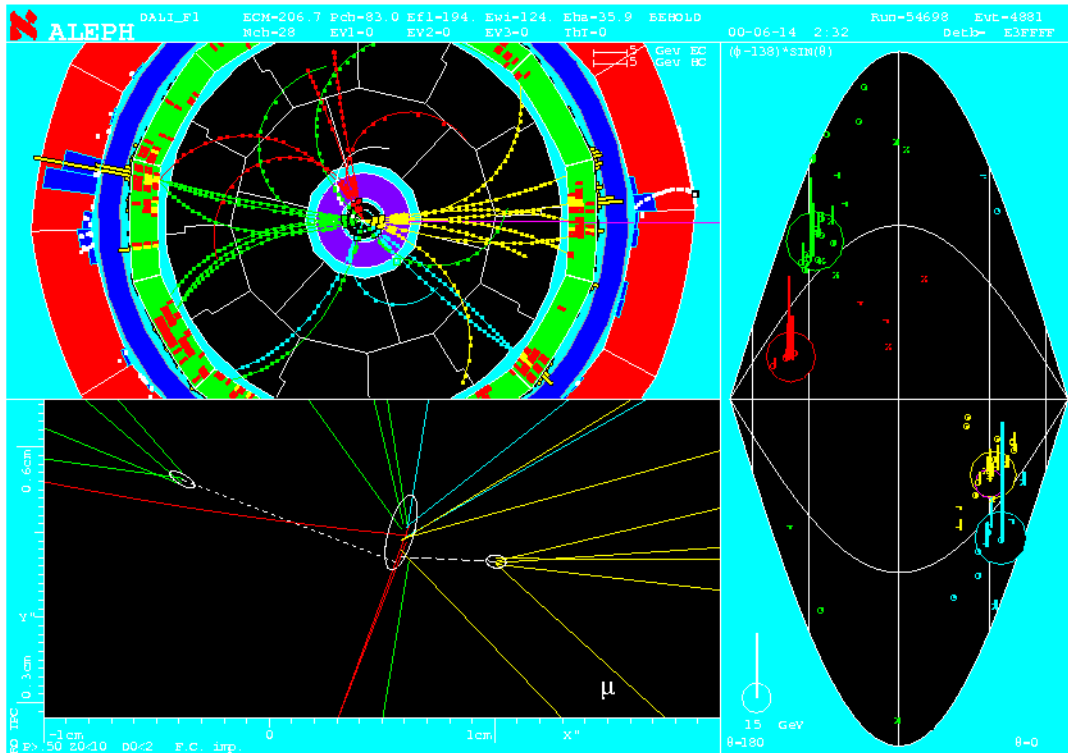
Figure 5. Higgs-like event detected by the ALEPH experiment at LEP: an e^+e^- collision produces 4 hadrons containing b quarks recognized by their secondary vertices due to longer lifetimes.

ATLAS[14] and CMS[15] were designed with the main aim of discovering the Higgs boson, ALICE[16] is specialized on heavy ion collisions and LHCb[17] on studying rare processes involving b quarks. The author belongs to CMS, so most of the results we mention are due to CMS, but all will be compared to those of ATLAS pointing out the similarities and the (very few and not significant) differences.

The ATLAS and CMS collaborations are really huge. According to the official statistics in 2012 CMS had 3275 physicists (incl. 1535 students) and 790 engineers and technicians from 179 institutions of 41 countries (ATLAS was even slightly larger). The biggest participant of CMS is the USA, then Italy, Germany and Russia. It is quite remarkable how similar and different are ATLAS and CMS. ATLAS uses a lot of new detector techniques while CMS consists of mostly traditional parts. CMS is based on the largest superconducting solenoid on Earth whereas ATLAS has a smaller solenoid encircled by 8 huge magnets making a toroidal field. CMS weighs 14000 tons, twice the weight of ATLAS in an order of magnitude smaller volume. And in spite of all these differences, the two collaborations get very similar results.

The design of LHC and its experiments started well before the actual start of LEP, which means that the construction of the LHC detectors took two decades of hard work before the actual data acquisition started. Its first two years LHC devoted to development rather than data taking, that really started in 2011 only.

Even before LHC started the parameter fitting of the Standard Model pointed toward a light Higgs boson, with a mass around 100 GeV/c^2. As LEP excluded the Higgs boson below 114 GeV/c^2 the LHC experiments had to be prepared for detecting the Higgs boson in the most
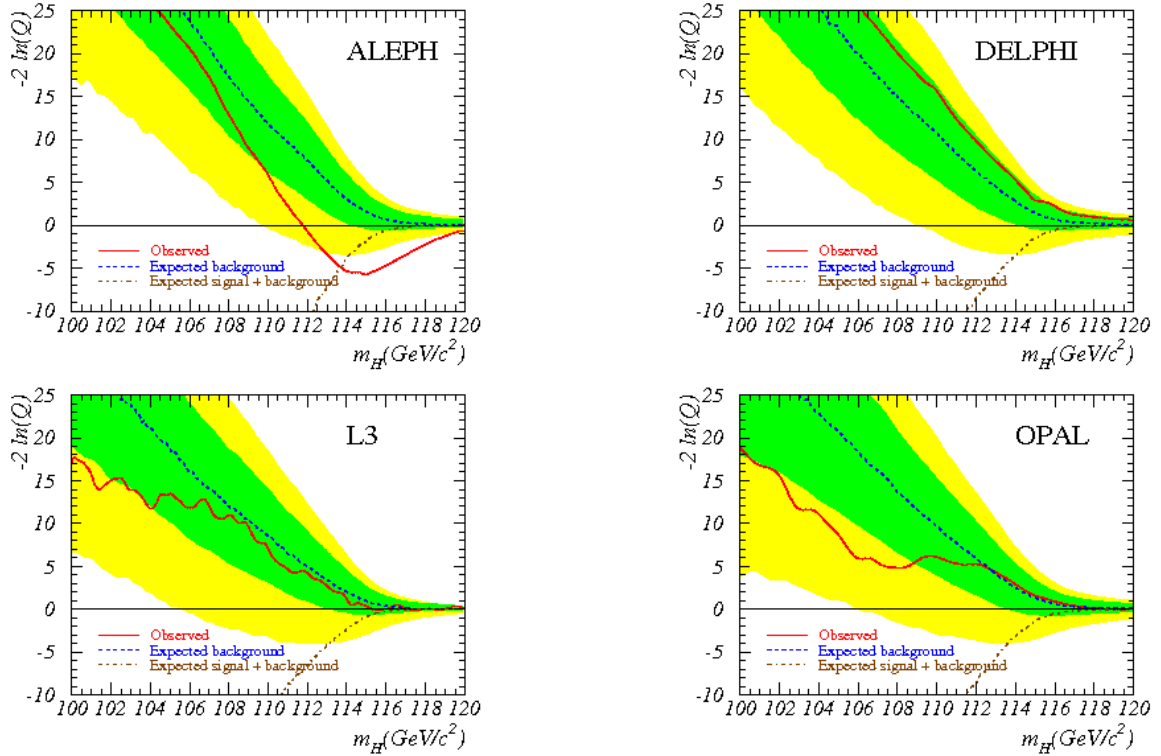
Figure 6. Exclusion of the Higgs boson at LEP. The test statistic, $-2\ln Q$ shows a significant signal for ALEPH and nothing for the other 3 LEP experiments at equivalent statistical and experimental circumstances. The observed signal of ALEPH by far exceeds the expectations of the Standard Model.

complicated mass region, around 120 GeV/c^2, with several competing decay channels (Fig. 4). It was shown very early that the best channels to observe a light Higgs boson at LHC should be two-photon, H→$\gamma\gamma$ and 4-lepton, H→ZZ*→$\ell^+\ell^-\ell^+\ell^-$ channels, because of the very high hadron background. Indeed, in 2012 the LHC luminosity was already so high that every bunch crossing (ie. every event) contained 10–20 p-p collisions leading to copious hadron production. Thus both large experiments, CMS and ATLAS designed their tracking systems and electromagnetic calorimeters with this in mind. The electromagnetic calorimeter of CMS consists of 75,848 PbWO$_4$ single crystal scintillators, whereas that of ATLAS is a sampling calorimeter based on liquid argon shower detectors.

By the beginning of 2012, when all 2011 data were analyzed, the possible mass of the SM Higgs boson was already confined to the region of $114 < M_{\mathrm{H}} < 127$ GeV/c^2 by CMS[18] (with very similar results from ATLAS). In that region 2– 3 σ excesses were found at $\sim$125 GeV/c^2 in the two main decay channels, H →$\gamma\gamma$ and H → ZZ. It seemed more and more probable that the Higgs boson will be observed at LHC in 2012, it was even decided by the CERN administration to extend the data taking scheduled for 2012 before the long shutdown for accelerator development if necessary for the discovery.

On July 4th, the beginning of the large annual high-energy physics congress in Melbourne, the spokespersons of ATLAS and CMS gave talks from CERN (in internet connection to the whole word, including, of course, the main auditorium of the Australian conference) on Higgs search. They announced that at LHC collision energies 7 and 8 TeV, in the two most significant
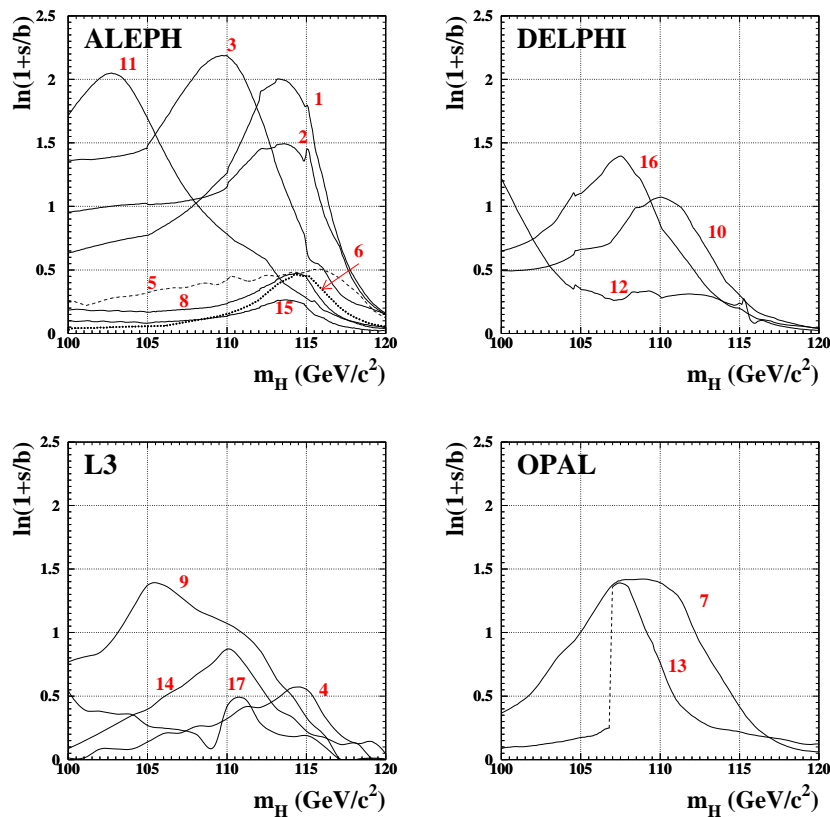
Figure 7. *Spaghetti diagrams* of 17 Higgs-like events detected by the 4 LEP experiments: signal weights against the simulated Higgs mass.[13] The ALEPH events crowd around 115 GeV/c^2 whereas for the other 3 experiments there are less of them with a rather random mass distribution.

decay channels H $\to \gamma\gamma$ and H $\to$ ZZ $\to \ell^+\ell^-\ell^+\ell^-$, at an invariant mass of $m \approx 126$ GeV a new boson is seen at a convincing statistical significance of 5σ confidence level each with properties corresponding to those of the Standard Model Higgs boson. The fact that the new particle could decay to two photons or Z bosons, confined its spin to an even integer, i.e. a boson of $S = 0$ or $S = 2$. Of course, as the data analysis was optimized to find the SM Higgs, it was very unlikely to find something very different. Nevertheless, the two experiments emphasized that it has to be studied, whether or not its spin is really zero with a + parity (the pseudo-scalar mesons have spin 0 with negative parity), and that its decay probabilities to various final states follow the predictions of the Standard Model. After reanalyzing their data the Tevatron experiments, CDF and D0 also found an excess[19] at this mass (after the LHC started the Tevatron accelerator of Fermilab was stopped).

6. Reactions of the Media
The saying that *three people can keep something secret only if two of them are dead* is attributed to Benjamin Franklin. As any result of a collaboration has to be approved by all members before it is made public, the more than 6000 participants of ATLAS and CMS knew well in advance the developing result. Thus two days before the 4th July announcement, *Nature Online* already reported the result.[20] Of course, the fact that the CERN management invited to the seminar all
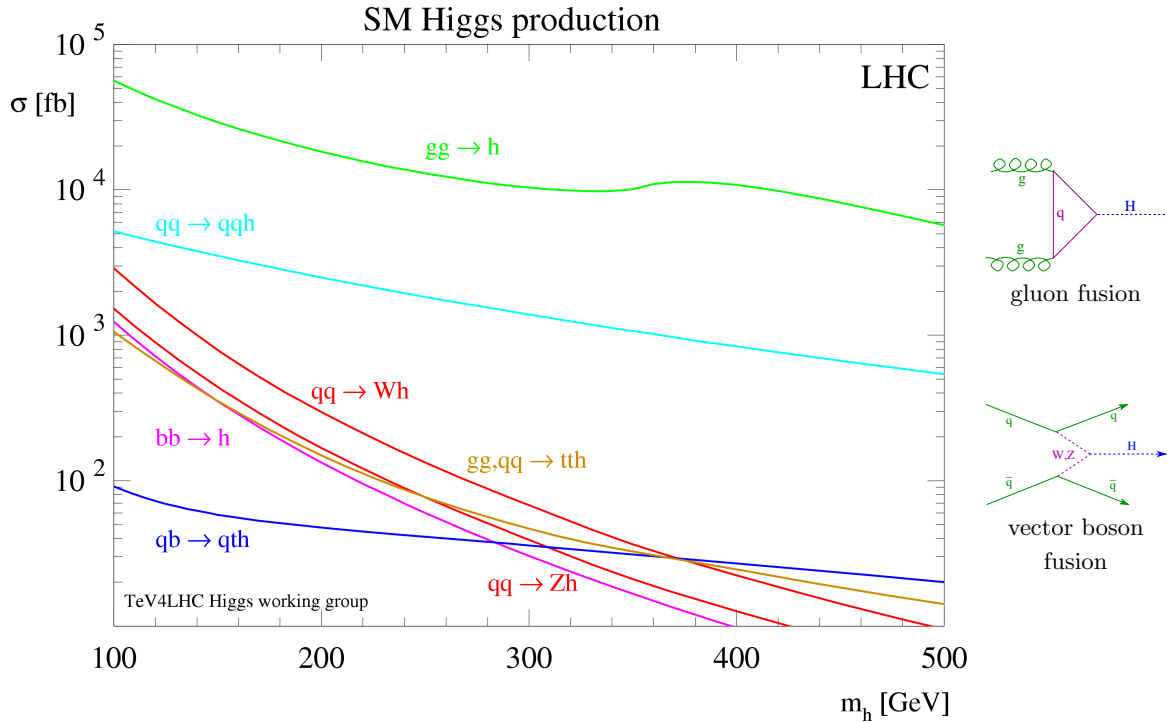
Figure 8. Formation of the SM Higgs boson in p-p collisions at LHC.

leading scientists of the field including the theoreticians who developed spontaneous symmetry breaking for the Standard Model also helped people to guess that something dramatic will be announced.

CERN produced some figures concerning the media echo of the day: 55 media organizations were represented at the talks of 4 July, the talks were broadcasted via close to half a million internet connections (many of them being conference rooms in partner institutions, e.g. three in Hungary with quite an audience in each), 1034 TV stations devoted 5016 news broadcasts to the event for more than a billion (10^9) people. Many-many news articles and even more blogs and talks discussed the conditions and importance of the discovery.

7. The observations

On 31 July the two experiments submitted papers of the discovery to Physics Letters B, they were published 14 August.[21,22] Both papers are 15 pages long followed by 16 pages of close to 3000 authors and both are dedicated to the memory of those participants who could not live to see the result of the more than two decades of construction work. Fig. 12 shows the di-photon spectra obtained by ATLAS and CMS in July 2012, after analyzing about a quarter of the data to be collected in 2012. The 4-lepton spectra were quite similar with less background and signal, they are shown in Fig. 13. Thus both experiments saw at the same invariant mass in both most significant decay channels the new boson. In all cases the signal strengths agreed within uncertainties to the predictions of the Standard Model.

What was really convincing of the observation was the distribution of the p-values of the events selected in the various analyzed decay channels of the hypothetical Higgs boson. For CMS it is shown in Fig. 14: the significance is already as high as 5σ for the data available in July 2012. It was a joke of statistics that in July 2012 adding together two decay channels, $H \to \gamma\gamma$ and $H \to 4\ell$ gave the same 5σ significance for both ATLAS and CMS whereas adding
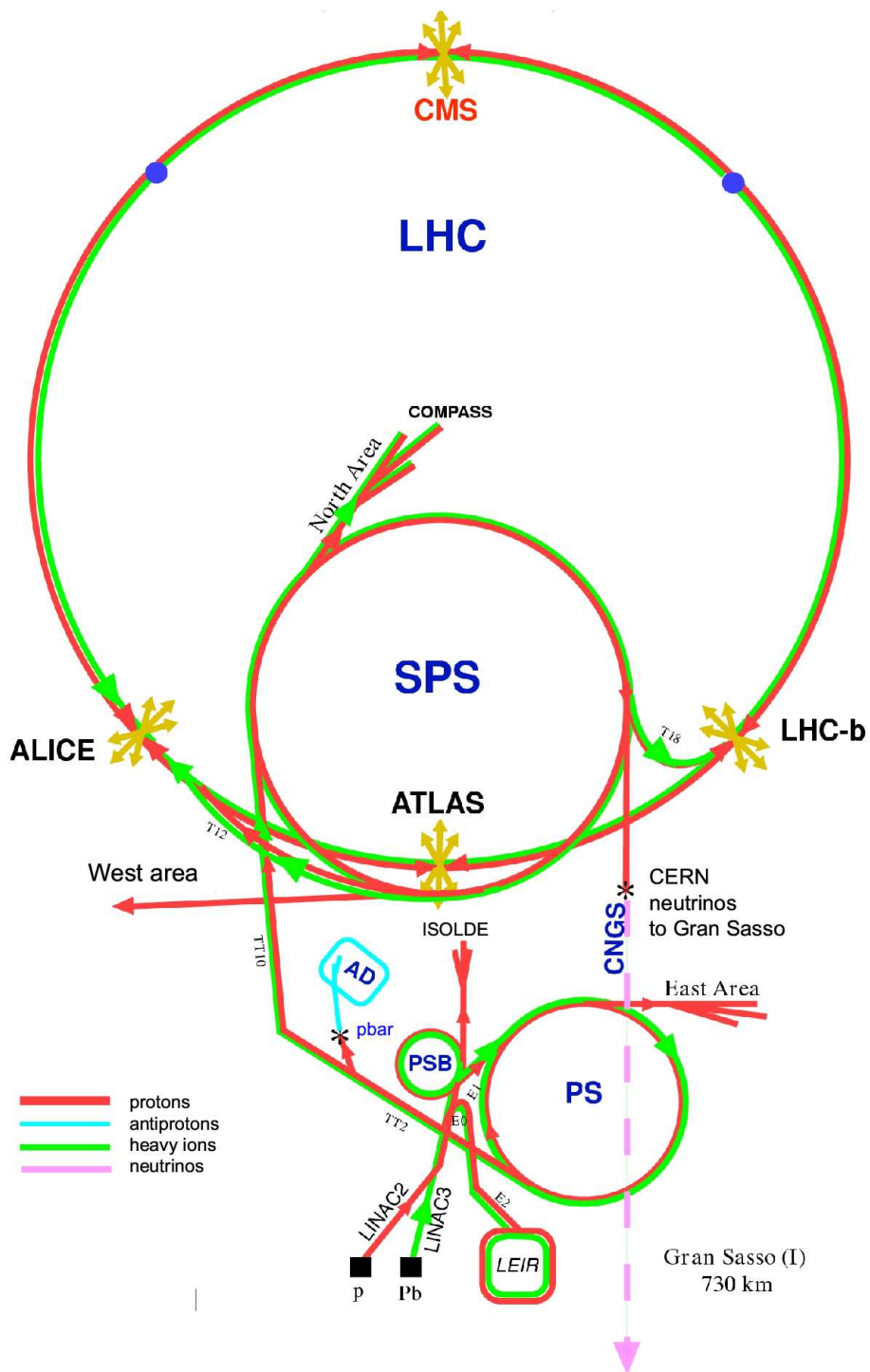
Figure 9. The accelerator complex of CERN with the Large Hadron Collider

to it the results for other channels increased the significance to 6σ for ATLAS and left it at 5σ for CMS (Fig. 14).
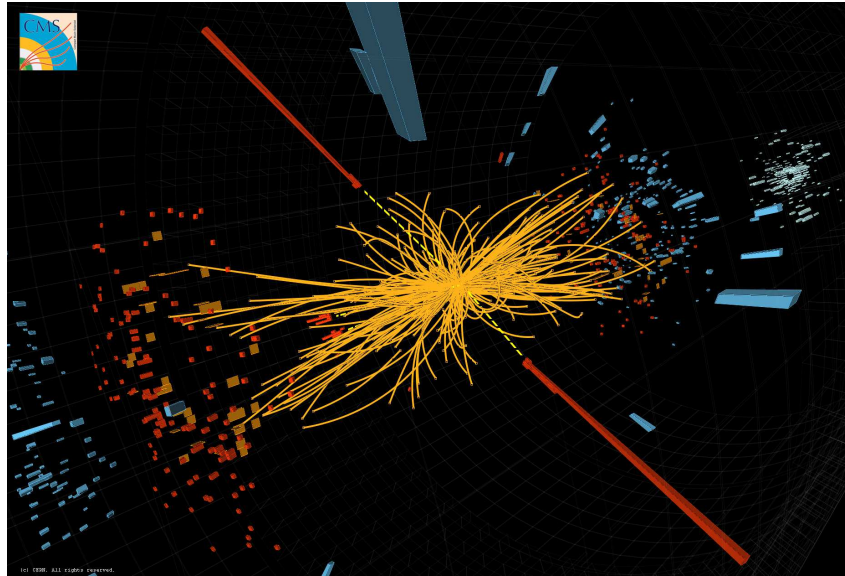
Figure 10. Higgs-like event detected by the CMS experiment at LHC: a boson is formed in a p-p collision and decays to 2 energetic gamma photons. The block sizes at the end of the invisible photon trajectories correspond to the photon energies deposited in the electromagnetic calorimeter.
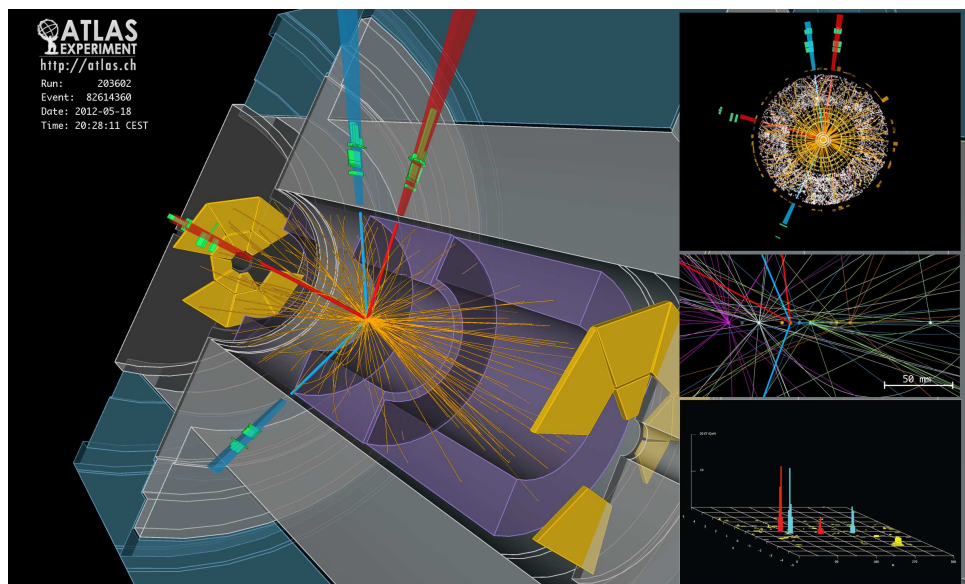

Figure 11. Higgs-like event detected by the ATLAS experiment at LHC: a p-p collision produces 4 electrons, one pair is from Z-decay as identified by the invariant mass. The 4-electron mass corresponds to a decaying mass of 125 GeV/c^2. Upper right: x-y view, lower right: lego plot of energy deposits in the calorimeters. Middle right shows that there were 9 other identified vertices of p-p collisions in the neighborhood of the candidate Higgs decay belonging to the same LHC bunch crossing.
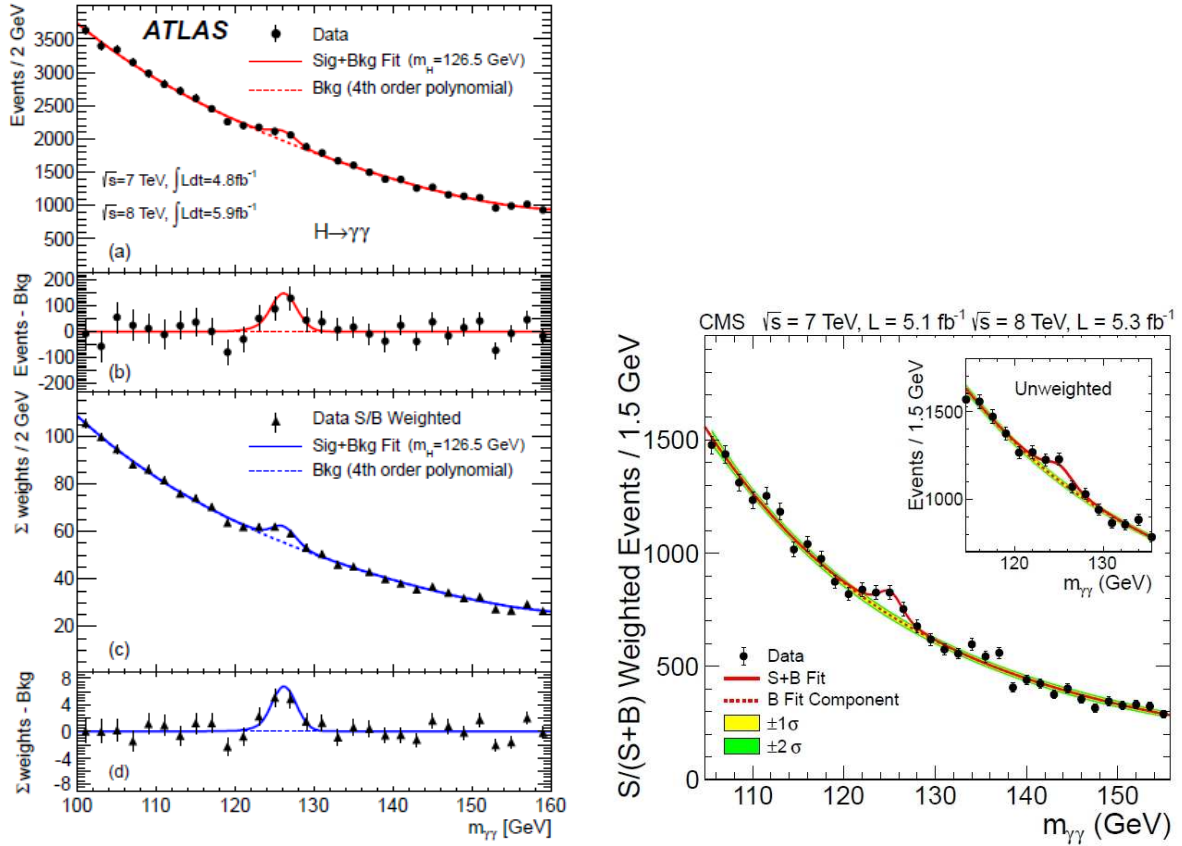
Figure 12. First observation of the Higgs-like boson by ATLAS[21] and CMS[22] in the $\gamma\gamma$ invariant mass distribution at 126 GeV/c^2. The amplitudes of both observed signals are close to the expectations of the Standard Model as shown by the fitted curves. Both experiments plotted the raw events and also the sum of event weights according to their signal-likelihood.

8. Is it really the Higgs boson?

Analyzing most of the data collected in 2012 confirmed the existence of the new boson and led to the conclusion that all observed properties of the newly discovered particle are within statistics close to those predicted for the Higgs boson of the Standard Model. The fact that it decays to two photons points to its having spin 0 or 2. The charged lepton spectra bears the features of its having $S = 0^+$ as ascertained by both experiments.[24,25] Its mass as determined by CMS,[26] the average of all decay channels is $< M_X >= 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{syst})$ (Fig. 15). The ATLAS result is almost exactly the same:[26] $125.5 \pm 0.2(\text{stat}) \pm 0.6(\text{syst})$. The differences in the uncertainties are due to the facts that ATLAS had more signal-like data, but also got more different masses in the two main channels. The measured signal strengths of the new particle are also compatible with that expected for the Standard Model Higgs boson: for CMS it is $\sim 20\%$ less while for ATLAS $\sim 40\%$ more than the SM prediction, but both deviations are within the experimental uncertainties. As a theoretician remarked whenever ATLAS has an excess CMS comes up for everybody's annoyance with a deficit, bringing the average close to the SM prediction.

The LHC experiments studied the cross sections of the processes connected to the new particle. Fig. 16 shows the signal strengths of production and decay in various possible channels
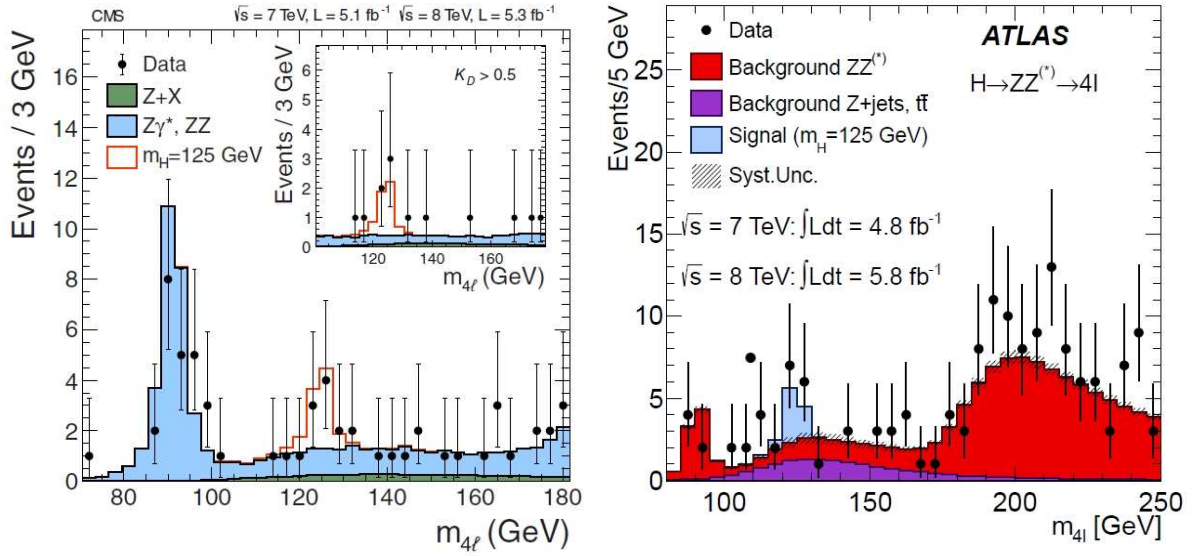
Figure 13. First observation of the Higgs-like boson by CMS[22] and ATLAS[21] in the $\ell^+\ell^-\ell^+\ell^-$ invariant mass distribution at 126 GeV/c^2. The amplitudes of the observed signals are close to the expectations of the Standard Model.
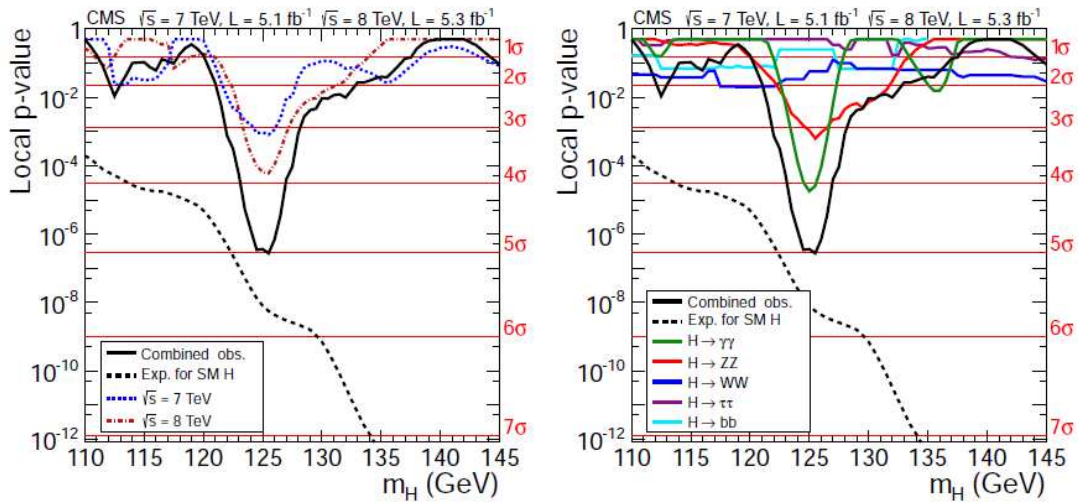

Figure 14. Observation of the Higgs-like boson by CMS[23] in the invariant mass distribution of p-values at 125 GeV/c^2 as based on the data collected at LHC at collision energies 7 TeV in 2011 and 8 TeV in 2012 (left) and in the various decay channels (right). The amplitude of the observed signal is close to the expectations of the Standard Model.

of the Higgs-like boson measured by CMS[23] as compared to those predicted by the Standard Model for the Higgs boson with a mass of 126 GeV/c^2. The amplitudes of all observed signals are in agreement with the expectations of the Standard Model. ATLAS got similar results, of course.

Thus what we found is very likely the Standard Model Higgs boson. On one hand this is
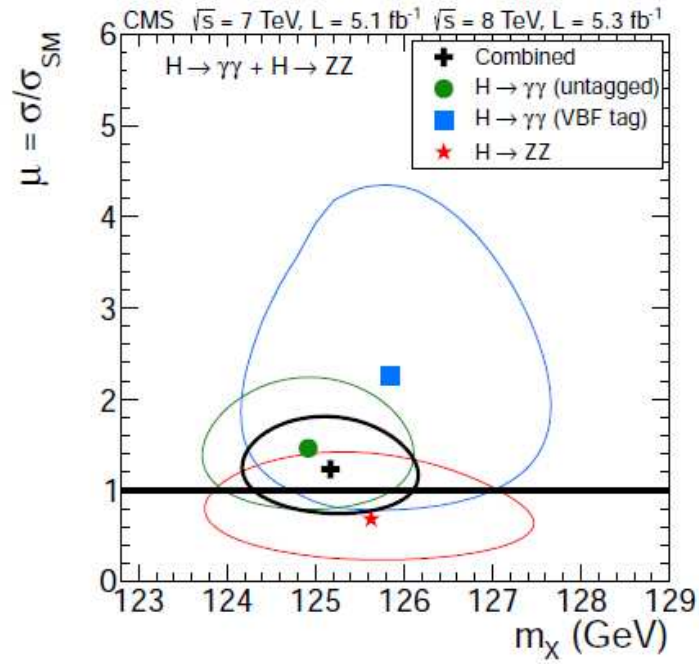
Figure 15. The relative signal strengths in the most significant decay channels normalized to the predictions of the Standard Model for $M_H = 125$ GeV against the invariant masses of the new boson as measured by CMS.[23] The two data points agree within statistics with each other and with the expectations of the Standard Model.
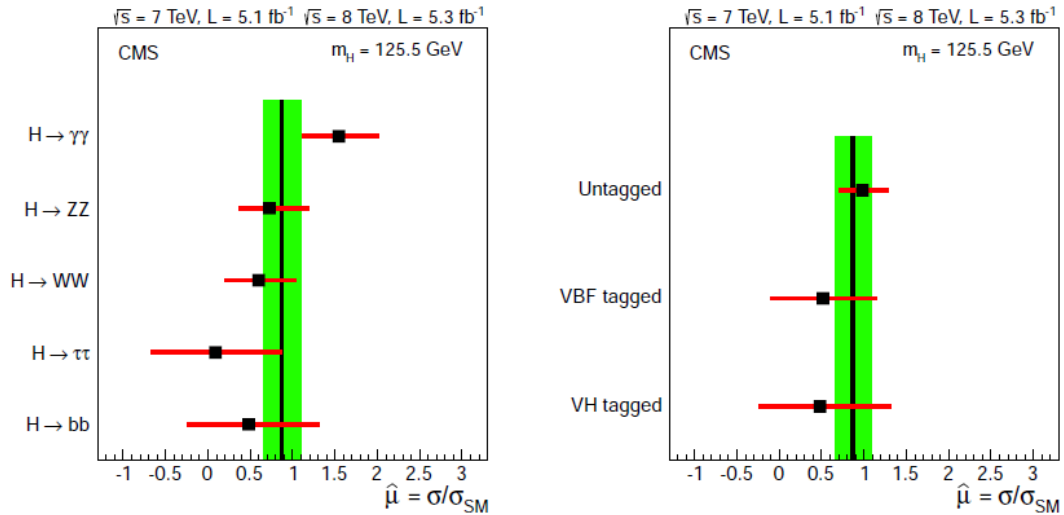

Figure 16. Signal strengths observed by CMS[23] for the Higgs-like particle in various possible decay (left) and production (right) channels as compared to those predicted by the Standard Model for the Higgs boson with a mass of 125.5 GeV/c^2.

a great success of particle physics. On the other hand this is somewhat of a disappointment as the SM has theoretical shortcomings which need new physics to resolve. Just to list a few of them: it cannot unite the interactions at large energies, cannot account for the dark matter of the Universe and cannot explain neutrino oscillations. There are many extensions of the theory which should result in deviations from the Standard Model. Most of those problems can be resolved e.g. by *supersymmetry*, but none of its predicted phenomena could be found yet experimentally. The observables of the Higgs boson should be sensitive to some of the features of new physics and these studies will be the main job of ATLAS and CMS in the future, from 2015 when the LHC will restart with twice the energy and luminosity of 2012.

It is very interesting that the 126 GeV mass of the Higgs boson seems to be exciting for theoreticians, there was even a special workshop[27] organized to discuss this mass in 2013. The reason is that $M_H = 126$ GeV is at the border line of the stability of electroweak vacuum on the plane of top mass against Higgs mass, see e.g.[28] At the Madrid workshop the apparent fine tuning of the Standard Model compelled some physicists to recall the anthropic principle.

9. The Nobel Prize
As the LHC discovery gradually ripened many people asked who will get the Nobel Prize if the Higgs boson is discovered. There were even rumors that the Nobel Committee might consider the give it to CERN and to the two collaborations, although that would have been against the Nobel tradition. By March 2013 it was already quite clear that the new particle is actually a Higgs boson and very probably that of the Standard Model. In the end of September 2013 the blogs started speculate about Higgs and Englert as Robert Brout passed away in 2011. Indeed, in October François Englert and Peter Ware Higgs received the 2013 Nobel Prize in physics "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."

10. Acknowledgments

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