Search for the Higgs boson:
a statistical adventure of exclusion and discovery

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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 talk we describe the search process: the exclusion of the Higgs boson at LEP, the Large Electron Positron collider, and the observation at LHC of a new boson with properties close to those predicted for the Higgs boson of the Standard Model. We try to pay special attention on the statistical methods used.

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. All fermions have antiparticles of opposite charges. 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 nuclei and of the neutron, 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

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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 introduce their masses. This spontaneous symmetry breaking (SSB) 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 Higgs–Englert–Brout–Guralnik–Hagen–Kibble mechanism [1].

The spontaneous symmetry breaking mechanism consists of adding to vacuum a potential which breaks its perfect symmetry. This 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 of the heavy weak bosons, W+, W- and Z0 mediating the weak interaction and also masses for the basic fermions, the quarks and leptons. The masses of the weak bosons are predicted by the Standard Model, whereas the fermion masses are not, those are free, adjustable parameters. Note that the masses of our macroscopic world are mostly due to the energy content of the proton and the neutron and not due to the SSB 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 Fig. 2 according to the LEP Electroweak Working Group [2]. 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.

Figure 3 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.

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

Figure 1. Spontaneous symmetry breaking: the Higgs potential. The axial symmetry of the potential is not violated by putting a ball on the top at zero, 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 \( \text{Im}(\Phi) = 0 \).
Figure 2. Parameters of the Standard Model [2] as determined by the experiment (2nd column) with uncertainties (3rd column), its prediction or fit by the Standard Model (4th column) and a bar plot showing the difference between theory and experiment divided by the experimental uncertainty. The agreement if purely statistical as the difference is in only one case more than 2 uncertainties.
Figure 3. Formation of the SM Higgs boson in p-p collisions at LHC.

told [3] “It was in 1972 ... that my life as a boson really began”.

2. Statistical Concepts of Particle Physicists

 Those 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 [4]. 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.

 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 experimental data are basically event counts, the basic concepts are Poisson-like. The data follow the Poisson distribution \( n_i \) events in bin \( i \): \( P(n_i|\mu_i) = \frac{\mu_i^n e^{-\mu_i}}{n_i!} \) and the result is usually expressed in terms of the Poisson likelihood: \( L = \Pi_i P(n_i|\mu_i) \), where the expected number of events is \( \bar{\mu}_i = \sum_j L \sigma_j \epsilon_{ji} \), \( L \) is the integral luminosity collected, \( \sigma_j \) is the cross section of source \( j \) and \( \epsilon_{ji} \) 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
What we usually try to observe is a resonance. For a particle with lifetime \( \tau = \Gamma^{-1} \) and decay rate \( \Gamma \) the event rate against the invariant mass of the decay products is

\[
\chi(E) = \frac{1}{(E-M)^2 + \Gamma^2/4}
\]

i.e. a Lorentz curve (Breit-Wigner resonance). It shows a peak at the invariant mass of the decaying system with a full width at half maximum \( \Gamma \). We claim the discovery of a new particle if we see a resonance at the invariant mass of the particle in all expected decay channels, by all means.

That \( \sigma \) 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: \( \sigma = \sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2} \)

Another important feature of high-energy data analysis is the blind analysis [6]: “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 110 \text{ GeV} \approx \Gamma \text{ GeV} \approx 140 \text{ GeV} (where \( M_H \) is the simulated Higgs mass) because of the 3\( \sigma \) 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 \( \Gamma \) the event rate against the invariant mass of the decay products is

\[
\begin{align*}
\chi(E) &= \frac{1}{(E-M)^2 + \Gamma^2/4} \\
\end{align*}
\]

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 \( \Gamma \). We claim the discovery of a new particle if we see a resonance at the invariant mass of the particle in all expected decay channels, by all related experiments.

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 \( 2 \cdot (\sqrt{N_S} + N_B - \sqrt{N_B}) \) [7]

- 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.
Figure 4. The definition of the p-value: how much is the observed excess above background as compared to the $\sigma$ uncertainty. We claim a discovery if that excess is above 5$\sigma$.

- 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 choose a test statistic. That could be any kind of probability variable characteristic of the given phenomenon: probabilities for having background only, signal or combinations. One of the favorite is the Q likelihood ratio of signal + background over background: $Q = \frac{L_{s+b}}{L_b}$. As you see, although our basic approach is definitely frequentist there is a certain Bayesian influence as well. What most frequently plotted is

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

Here the variables are the following:

- $n_k$: events observed in channel $k$, $k = 1 \ldots N_{ch}$.
- $s_k(m_H)$ 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 (Fig. 4). Translated to our language that means the probability that random fluctuation of the measured background could give the observed excess.
4. Exclusion at LEP
Although the four large experiments at the Large Electron Positron (LEP) collider saw no new physics, no 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.

At LEP the dominant formation process is Higgs-strahlung $e^-e^+\rightarrow ZH$ (the name comes from the funny English word Bremsstrahlung) 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 in the 4 interaction points of the electron-positron collider, ALEPH, DELPHI, L3 and OPAL (the present author was in OPAL). The structure of the large 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 the 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 muons leaving the system. All detectors have huge magnets encompassing as much as possible of the detector parts.

Statistics played a rough joke at LEP: one of the experiments, ALEPH, saw in one of the 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 (Fig. 6, [8]). ALEPH saw the excess in the 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. The b quark is identified by its long lifetime leading to a secondary decay vertex in the event. Another strange thing was that the
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.

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 [8]. 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. Observation at LHC
Just like LEP had, the Large Hadron Collider has also 4 interaction points with a major experiment (and possibly smaller ones) in each. The two largest ones, ATLAS [9] and CMS [10] were designed with the main aim of discovering the Higgs boson, ALICE [11] is specialized on heavy ion collisions and LHCb [12] on studying rare processes involving $b$ quarks. The
Figure 7. *Spaghetti diagrams* of 17 selected events for the 4 LEP experiments: signal weights against the simulated Higgs mass [8]. 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.

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. These collaborations are 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. The largest participant country was the USA, then Italy, Germany and Russia.

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 complicated mass region, around 120 GeV/$c^2$, with several competing decay channels. It was shown very early that the best channel to observe a light Higgs boson at LHC should be the decay to 2 photons because of the very high hadron background. Thus both large experiments, CMS and ATLAS designed their electromagnetic calorimeters with this in mind. The CMS one
consists of 75,848 PbWO₄ single crystal scintillators, whereas the electromagnetic calorimeter ATLAS is a sampling one 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_H < 127 GeV/c² by CMS [13] (with very similar results from ATLAS). In that region 2...3σ excesses were found at ∼125 GeV/c² in the two main decay channels, H → γγ and H → ZZ. After reanalyzing their data the Tevatron experiments, CDF and D0 also found an excess at this mass (after the LHC started the Tevatron accelerator of Fermilab was stopped). 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.

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 two decay channels H → γγ and H → ZZ → ℓ⁺ℓ⁻ℓ⁺ℓ⁻, at an invariant mass of m ≈ 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.

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 two large experiments knew well in advance the developing result. Thus two days before the 4th July announcement, Nature Online already reported the result [14]. Of course, the fact that CERN invited all leading scientists of the field including those 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 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 (10⁹) 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 [15, 16]. 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. 8 shows the di-photon spectra obtained by CMS in July 2012, after analyzing about a quarter of the data to be collected in 2012. The 4-lepton spectra are quite similar with less background and signal, for CMS it is shown in Fig. 9.

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
8. Is it the Higgs boson?
Analyzing most of the data collected in 2012 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 $S = 0^+$ [17]. Its mass as determined by CMS [18] by the average of all decay channels is $< M_X > = 125.7 \pm 0.3 \text{(stat)} \pm 0.3 \text{(syst)}$. The ATLAS result is almost exactly the same: $125.5 \pm 0.2 \text{(stat)} \left\{ \begin{array}{c} +0.5 \\ -0.6 \end{array} \right\} \text{(syst)}$. The difference in the uncertainties are due to the facts that (i) ATLAS had more signal-like data, but (ii) got more different masses in the two main channels. The signal strengths of the new particle is also compatible with that expected for the Standard Model Higgs boson: for CMS it is $0.80 \pm 0.14$ and for ATLAS $1.43 \pm 0.16 \text{ (stat)} \pm 0.14 \text{ (syst)}$. 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. 11 shows the signal strengths of production and decay in various possible channels.
Figure 9. Observation of the Higgs-like boson by CMS [16] in the $\ell^+\ell^-\ell^+\ell^-$ invariant mass distribution at 125 GeV/$c^2$. The amplitude of the observed signal is close to the expectations of the Standard Model.

of the Higgs-like boson measured by CMS [18] as compared to those predicted by the Standard Model for the Higgs boson with a mass of 125 GeV/$c^2$. The amplitudes of all observed signals are in agreement with the expectations of the Standard Model.

Thus what we found is very likely the Standard Model Higgs boson. On one hand this is 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. All 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 [19] 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. [20]. At the Madrid workshop the apparent fine tuning of the Standard Model compelled some physicists to recall the anthropic principle.
Figure 10. Observation of the Higgs-like boson by CMS [18] in the invariant mass distribution of p-values in a wide range and closer to $125 \text{ GeV}/c^2$ as based on the data collected at LHC in 2011 and 2012. The amplitude of the observed signal is close to the expectations of the Standard Model.

Figure 11. Signal strengths of production and decay in various possible channels of the Higgs-like boson measured by CMS [18] as compared to those predicted by the Standard Model for the Higgs boson with a mass of $125 \text{ GeV}/c^2$.

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