The pre-LHC Higgs hunt

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Enormous efforts at accelerators and experiments all around the world have gone into the search for the long-sought Higgs boson, postulated almost five decades ago. This search has culminated in the discovery of a Higgs-like particle by the ATLAS and CMS experiments at CERN’s Large Hadron Collider in 2012. Instead of describing this widely celebrated discovery, in this article I will rather focus on earlier attempts to discover the Higgs boson, or to constrain the range of possible masses by interpreting precise data in the context of the Standard Model of particle physics. In particular, I will focus on the experimental efforts carried out during the last two decades, at the Large Electron Positron collider, CERN, Geneva, Switzerland, and the Tevatron collider, Fermilab, near Chicago, IL, USA.

1. Introduction

In the following, I give a historical overview of the experimental efforts carried out over several decades in order to find one (or more) Higgs boson(s) or to exclude its existence. In the end, it took almost five decades from the postulation of the mass mechanism [1–6] and the existence of a massive boson [3,5] to its discovery by the Large Hadron Collider (LHC) experiments ATLAS and CMS [7,8]. Equally interesting and fascinating as the discovery itself has been the experimental road towards it, which started in the 1980s and which has seen various protagonists along its path. Here, I will try to give an account of the achievements by the main protagonists, namely the experiments at CERN’s Large Electron Positron (LEP) collider in Geneva, Switzerland, and those at Fermilab’s Tevatron collider near Chicago, IL, USA. Furthermore, I will recall how a large set of highly precise particle collision data, accumulated by those and other experiments, allowed the range of possible Higgs boson masses to be rather tightly constrained, under the assumption that such a boson indeed exists as predicted by the Standard Model (SM).
of particle physics. This approach was strongly motivated by the impressive success of the SM for describing, often to an astonishing degree of precision, the very large set of experimental observations in particle physics experiments.

The SM is a quantum field theory, built on the powerful principle of gauge invariance [9–11]. It describes the fundamental building blocks of matter (quarks and leptons), as well as the interactions among them which are mediated by gauge bosons, which are particles with unit spin. The mediator of the electromagnetic interaction is the photon, the mediators of the strong interaction among quarks inside protons and neutrons are the gluons, while the gauge bosons responsible for weak interactions are the heavy $W$ and $Z$ bosons. Indeed, the fact that the $W$ and $Z$ bosons are so massive, while the photon is massless, is a manifestation of the breaking of electroweak symmetry, which is at the heart of the unification of electromagnetic and weak interactions. This has resulted in a plethora of theoretical attempts (not only in the 1960s) to find mechanisms that can explain this breaking of electroweak symmetry and, if possible, to also explain how the matter particles acquire mass, while at the same time preserving all the good properties of the theory, in particular gauge symmetry and renormalizability. One ‘simple’ solution to this problem consists in the introduction of an additional scalar (spin zero) particle, called the Higgs boson, which interacts with matter particles and gauge bosons and thus explains their masses in a dynamical manner. Obviously, for many years, the main question remained that if this particle exists, if indeed it exists at all, what its mass would be. Indeed, while the SM predicts all relevant details regarding the interaction of the Higgs boson with other particles, it does not predict its mass. Only experiment would be able to give a definite answer.

Fortunately, theoretical considerations help to constrain somewhat the mass range over which such an experimental search should be performed. An example for such theoretical constraints can be found in [12]. The SM can be conceived as an effective theory that provides reliable predictions for particle interactions up to a certain energy (or equivalently short distance) scale, but that might have to be replaced by a more fundamental theory at energy scales beyond a given threshold $\Lambda$. For example, let us assume that the SM is valid up to an energy scale of $\Lambda \sim 10^9$ GeV, which corresponds to distance scales of approximately $10^{-24}$ m.¹ By studying the properties of the SM expected at such an energy scale $\Lambda$, and in particular the properties of the Higgs sector within the SM, it turns out that the Higgs boson mass should fall within a range of approximately 130–230 GeV (we use natural units here, meaning $c = \hbar = 1$). The lower bound arises by requiring stability of the vacuum, i.e. stability of the ground state of the theory and thus, if the theory is correct, the ground state of the Universe. The upper bound results from considerations related to the predictive power of the resulting theory (perturbativity and triviality).

While these theoretical constraints should not be mistaken for strong evidence or proof that the Higgs boson should indeed be found within a certain mass range, they nevertheless give useful guidance to the experiments. In particular, if no assumptions are made for the validity of the SM beyond the experimentally achievable energy scales, namely of order 1 TeV or several hundreds of GeV, then the considerations above lead to a possible Higgs mass range from almost vanishing mass up to approximately 1 TeV. In fact, in the following, I will describe how this mass range has been probed by different experiments. Direct searches at LEP have covered (and excluded) Higgs masses from about 0 up to 114 GeV, the direct searches at the Tevatron were mostly sensitive to a Higgs boson with mass between approximately 100 and 180 GeV, while indirect constraints from precision data indicated that the Higgs boson should be rather light (approx. 100 GeV or so), while higher masses, in particular above 160–170 GeV, were disfavoured.

It is worth noting that much more detailed reviews and discussions of the historical developments can be found in [13–20].

¹Note that this is about a million times higher in energy, or smaller in distance, than that which can be probed at the most powerful accelerator (microscope) in the world, the LHC.
Figure 1. Feynman diagrams for processes as measured or searched for at LEP. (a) $e^+e^-$ annihilation into a $Z$ boson and subsequent decay into a fermion–antifermion pair and (b) the Higgs-strahlung process, where the Higgs boson is radiated off a $Z$ boson.

2. Experimental sites

The main sources of data for the Higgs search, prior to the LHC, were the experiments at the LEP collider at CERN and the Tevatron collider at Fermilab. LEP was installed near Geneva in Switzerland, in a circular tunnel of approximately 27 km circumference—the very same tunnel which hosts the LHC today. From 1989 to 1995, the accelerator was operated at centre-of-mass energies close to the mass of the $Z$ boson (91 GeV). This so-called LEP1 era gave rise to about 15.5 million electron–positron annihilations into a $Z$ boson, with subsequent hadronic decay ($e^+e^- \rightarrow Z \rightarrow q\bar{q}$, where the quark $q$ and antiquark $\bar{q}$ fragment into so-called jets of hadrons), as well as to approximately 1.7 million leptonic $Z$ decays ($e^+e^- \rightarrow Z \rightarrow \ell^+\ell^-$, with electrons, muons and taus as final state leptons $\ell$) (figure 1a). These events were recorded by the four experiments ALEPH, DELPHI, L3 and OPAL. The high statistics data sample allowed for very precise measurements and studies of the $Z$ resonance, as will be discussed later. Then, starting in summer 1995, the collider energy was continuously increased, from 130 GeV up to approximately 206 GeV reached in 2000. During the LEP2 era the experiments continued the study of fermion–antifermion production², but, more interestingly, at higher centre-of-mass energy new physics channels became accessible, such as the production of a pair of $W$ or $Z$ bosons. Also, the Higgs search became a central theme of the activities, as discussed below.

The Tevatron at Fermilab near Chicago was a proton–antiproton collider, installed in a ring of approximately 7 km circumference and operated from 1983 up to September 2011. Most relevant for the later discussion of Higgs searches at this accelerator was its Run II period (2001–2011), during which proton–antiproton collisions at a centre-of-mass energy of 1.96 TeV were recorded by the two experiments CDF and DØ. The spectrum of physics processes studied at a hadron collider such as the Tevatron or the LHC is much richer and more complicated than an $e^+e^-$ machine. In fact, space constraints prevent a discussion of the Tevatron physics programme here. However, just to mention one of the interesting processes, with some resemblance to those at LEP, $Z$ bosons can also be produced in proton–antiproton collisions and subsequently decay to, for example, lepton–antilepton pairs. However, in contrast to LEP, here the $Z$ boson can be accompanied by one or more hadronic jets from initial- or final-state gluon radiation, as well by further hadronic activity due to the so-called underlying event. I mention this type of process since it turned out to be important to the Higgs search, as discussed later.

3. The pre-LEP history

Interestingly, it took about a decade from the original formulations of the Higgs mechanism until the first comprehensive phenomenological study of Higgs production and decay was

²Fermions, such as leptons and quarks, are particles with spin $1/2$. 

carried out in 1975 [21]. In their paper, J. Ellis, M. K. Gaillard and D. V. Nanopoulos made a thorough investigation of the different processes for the production and subsequent decay of the hypothetical Higgs boson. Here we find the first calculation of the so-called Higgs-strahlung process (figure 1b), $e^+e^- \rightarrow Z^* \rightarrow ZH$, which turned out to be the main channel for the Higgs search at LEP. Also, they calculated important contributions to the quantum-loop-induced Higgs decay to two photons, which was shown to be a key process for the LHC Higgs search and which also influenced the design of the LHC experiments. Finally, in their paper they evaluated the set of existing data in order to put upper limits on the Higgs mass (e.g. a Higgs mass below 13 MeV could be excluded from the studies of neutron–nucleus scattering) and proposed further processes to access possible larger Higgs masses. Worth noting is the concluding paragraph of their paper, where they close with the following statements [21, p. 334]: ‘We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, ... and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up’. Thus, in hindsight, it appears that sometimes it may be better not to listen to our friends from theory.

In order to have an overview of the situation prior to the start of LEP, in terms of Higgs searches, it is instructive to read the ‘Review of particle properties’, as compiled by the Particle Data Group (PDG) in 1988 [22]. There we find that ‘in summary, the only cast-iron constraint on the Higgs mass is $M_H > 14$ MeV ... A combination of theoretical arguments and bounds from $B, \Upsilon$ and $K$ decays probably excludes the range below 4 GeV’ [22, p. 256]. As mentioned before, the 14 MeV constraint mostly resulted from measurements of nucleon–nucleus scattering, which would have been modified by long-range effects if a light Higgs boson existed. The measurements of $B, \Upsilon$ and $K$ decays were carried out by experiments at the Paul Scherrer Institute in Switzerland (SINDRUM), Cornell University, Ithaca, NY, USA (CLEO, CUSB) and CERN (CERN–Edinburgh–Mainz–Orsay–Pisa–Siegen Collaboration), as is nicely summarized in [13]. The cautious statement by the PDG regarding the 4 GeV limit was mainly due to large theoretical uncertainties on the possible decays of a very light Higgs boson. Thus, at the start of LEP in 1989, basically the whole range of Higgs boson masses, from very small values up to the kinematical limit, was open for exploration.

4. Direct searches at LEP

As already mentioned above, during the first years of operation the LEP centre-of-mass energy was tuned to the peak position of the $Z$ resonance (LEP1), while later it was continuously increased in order to probe $e^+e^-$ collisions well above the $Z$ resonance (LEP2). Throughout all those years, fermion–antifermion production as depicted in figure 1a remained the dominant process. On the other hand, the most relevant production mechanism for a Higgs boson was predicted to be Higgs-strahlung, as shown in figure 1b. Here a Higgs boson is produced in association with a $Z$ boson, which can be either off- or on-shell, depending on the overall kinematical constraints, i.e. depending on the particular centre-of-mass energy and the hypothesized mass of the Higgs boson. The most relevant Higgs decay channel sought was its decay into a bottom–anti-bottom quark pair ($H \rightarrow b\bar{b}$), since this decay has by far the largest branching ratio for Higgs masses accessible at the centre-of-mass energies of LEP, namely up to $M_H \sim 115$ GeV. Such $b$-quarks fragment into $b$-hadrons (particles containing at least one $b$-quark), which are short lived with an average lifetime of order 1.5 ps. As a consequence, $b$-hadrons travel distances of up to several millimetres away from the main interaction point, before they decay into other particles which are then tracked throughout the detector. In order to efficiently detect such decays, obviously it is important to have very precise tracking detectors, allowing the exact position of the vertices of tracks, i.e. those points where the extrapolated track directions intersect.
to be determined at a precision of tens of micrometres. Experimental requirements of this kind led to a significant boost for the development and deployment of novel high-precision silicon strip-detectors early in the LEP era. The success of this detector technology then also had a significant impact on the later design of the tracking systems of the LHC detectors.

During the LEP1 phase, the Higgs search was characterized by a very small signal-to-background ratio before any selection. For a Higgs mass of 30 GeV, the Higgs production cross section would be about four orders of magnitude smaller than the resonant process $e^+e^- \rightarrow Z \rightarrow f\bar{f}$, and this ratio decreases for larger Higgs masses. For example, about 10 signal events were expected by all four experiments together, for a Higgs mass of 65 GeV. This is to be compared with an overall background of about 15.5 million hadronic $Z$ decays. On the other hand, because of the rather different final states for signal and background, analyses could be designed which allowed the strong suppression of basically all backgrounds. The signatures sought were, for example, mono-jet events, where a jet of hadronic particles (as possibly arising from a Higgs decay) would not be balanced in energy and momentum by other hadronic activity in the event. Such a lack of visible particles could arise when the $Z$ boson, produced in association with the Higgs boson, decays into a pair of very weakly interacting neutrinos, which cross the detector without leaving any detectable signals. Another search channel consisted in the appearance of two b-tagged jets from the Higgs decay, i.e. two hadronic jets with an indication of secondary vertices and thus the presence of b-hadrons, together with a muon–antimuon pair consistent with a $Z$ boson decay or again missing energy due to a $Z$ decay into neutrinos. The missing-energy channels turned out to be the most powerful ones. At the end of LEP1, no excess of events was observed in either of the experiments, and the results were combined to yield a lower limit on the Higgs boson mass of 65.6 GeV (see [23] and references therein).

During the LEP2 phase, the main event signatures sought were again classified according to the decays of the $Z$ boson, with the hypothetical Higgs boson reconstructed from its decay into two b-tagged jets. The channel with the largest branching ratio (approx. 64%) consisted of four-jet events, with two b-jets from the Higgs and two further hadronic jets from the $Z$ boson. The second largest branching fraction (approx. 18%) resulted from events with two b-jets and missing energy/momentum from the $Z$ decay to neutrinos, while in the third case the leptonic decay of a $Z$ gives a lepton–antilepton pair together with two b-jets (approx. 9%). In contrast to LEP1, at LEP2 the selection of such signal events suffered from large irreducible backgrounds, mainly due to the production of a pair of $Z$ bosons ($e^+e^- \rightarrow ZZ$), where the various $Z$ decays give rise to exactly the same final states. This difficulty boosted, in a significant manner, the development of so-called multi-variate analyses, which combine in an optimal way the available information from measured event properties and thus provide a better signal to background separation than the more traditional analyses, based on sequential applications of selection cuts on relevant observables. Indeed, thanks to the deployment of such analysis techniques, signal-to-background ratios of about 1/1 to 2/1 could be achieved in the end, with the four-jet category giving the strongest sensitivity.

The maximally achievable LEP beam energy became an important focus of the activities. From kinematical considerations, the largest detectable Higgs boson mass is roughly given by the relation $M_H \approx \sqrt{s} - M_Z$, with $\sqrt{s}$ the centre-of-mass energy and $M_Z$ the mass of the $Z$ boson. Thus, as an example, a centre-of-mass energy of 206 GeV would allow for the production of a Higgs boson of mass up to about 115 GeV. The beam energy varies roughly with the fourth root of the number of accelerating radio frequency (RF) cavities. By the year 2000, 288 superconducting RF cavities and 56 room-temperature copper cavities were installed in the LEP ring, giving an accelerating gradient of 3630 MV per turn and thus a maximum beam energy of 209 GeV. Indeed, such an energy was reached in 2000, though only for short periods of time, and the main luminosity was rather accumulated for an average energy of about 206 GeV.

Up to the year 2000, none of the experiments had produced a significant excess of events compared with the background expectations, which resulted in a lower limit on the Higgs mass of 108.6 GeV. Then, by mid-summer 2000, the ALEPH experiment had recorded one high-mass
Figure 2. (a) Display of a Higgs candidate event from the four-jet category, recorded by the ALEPH experiment and (b) combination of the reconstructed Higgs mass distributions for all channels and all LEP experiments (adapted from [24]).

four-jet signal event candidate, corresponding to a reconstructed Higgs mass of about 114 GeV. By 5 September, two more such four-jet events (figure 2a) were found by ALEPH. This triggered considerable excitement and a slight extension of the final LEP run up to 3 November, allowing the data sample at a centre-of-mass energy of approximately 206 GeV to be increased by 70%. The final compilation of the results from all four experiments gave the following picture: out of the 10 detected events with the largest signal-to-background ratio expected for a Higgs boson with $M_H = 115$ GeV, seven were four-jet candidates with six of them recorded by ALEPH. A rather disputed candidate, with high signal-to-background ratio, was seen by L3 in the missing energy channel. Two of those 10 events were found by OPAL and one by DELPHI. When plotting the reconstructed Higgs mass as measured from the most significant events, adding up the observations from all four experiments, the distribution shown in figure 2b was obtained. Already by eye it is evident that the data are consistent with both hypotheses, namely the appearance of a Higgs boson with mass close to 115 GeV, as well as the background-only hypothesis. A more thorough statistical analysis finally gave the following result [24]: for a Higgs mass hypothesis of 115 GeV, the so-called $p$-value for the background-only hypothesis is 9% when combining the results of all four experiments. This $p$-value can be interpreted as the probability of wrongly rejecting the background-only hypothesis and corresponds to a significance of the observed excess of events of less than two standard deviations. This is by far not enough to claim evidence or even observation of a new particle, the latter rather requiring a $p$-value of $3 \times 10^{-7}$ or five standard deviations. The data from the ALEPH experiment alone showed an excess at the level of three standard deviations, while the OPAL and DELPHI observations were rather background-like, leading to the smaller significance in the final combination. Thus, the Higgs boson was not found at LEP, and the data were rather interpreted in terms of a lower limit on the Higgs mass of 114.4 GeV. Altogether this experience also showed the importance of having more than one experiment measuring the same type of events and allowing the data to be combined.

It is worth noting that, with 100 additional superconducting cavities, a centre-of-mass energy of 220 GeV could have been reached at LEP, thus giving access to Higgs boson masses of up to about 129 GeV (1), as had already been proposed in the early 1990s (e.g. [16,17]). Such an increase in energy was motivated by rather firm predictions by the minimal supersymmetric extension of the SM, indicating that the lightest supersymmetric Higgs boson should have a mass below 130 GeV [25]. However, as summarized by Hubner [26, p. 187], 'the maximum energy of LEP 2 was determined by the decision in 1996 to discontinue the industrial production of the superconducting cavities. Whether the potential of LEP should have been better fully exploited
up to its reasonable limit of 220 GeV in the centre of mass and whether this would have lead \[sic\] to the discovery of the Higgs particle as a number of models seemed to suggest \[17,27\], is a matter of speculation. The quest for the Higgs particle will hopefully end with the results obtained by the Tevatron and the LHC. In any case, LEP will stand as a landmark in the development of particle accelerators’.

5. Direct searches at the Tevatron

While the signal-to-background ratios at LEP, before any selection, were already rather small, at a hadron collider the challenge is even bigger. The total inelastic cross section in proton–antiproton collisions, due to processes mediated by strong interactions, is more than 10 orders of magnitude larger than the cross section for Higgs boson production. In order to have the slightest chance to get sensitivity to such a tiny signal, processes are addressed which are relatively easy to trigger on and which allow to discriminate against the overwhelming background of events with hadronic jets. Typically, these are processes involving electrons or muons, which carry a large momentum transverse to the beam axis and which are well isolated from other hadronic activity in the event. For example, one of the relevant processes sought at the Tevatron, for a Higgs boson with mass around 120 GeV, is the associated production of a Higgs and a Z or W boson, with the Higgs decaying into a bottom–anti-bottom quark pair, and the Z or W decaying leptonically, i.e. \( Z \rightarrow \ell^+\ell^- \) or \( W^\pm \rightarrow \ell^\pm v_\ell \). For larger Higgs masses around 160 GeV, the most sensitive channel turned out to be Higgs production via gluon fusion (a quantum-loop-induced process), with the Higgs boson decaying to a pair of W bosons, which in turn decay leptonically, i.e. \( gg \rightarrow H \rightarrow W^+W^- \rightarrow \ell^+v_\ell \ell^-v_\ell \).

Despite the fact that such leptonic channels help to reduce the backgrounds, the overall challenge is still huge. For example, in a sample of 1 fb\(^{-1}\) of accumulated data before any further event selection, the fraction of \( ZH \rightarrow \ell^+\ell^- b\bar{b} \) events compared with everything else is in \( 10^{14} \) ! Therefore, efforts were focused on maximizing the signal acceptance and efficiency, in order not to lose any signal event. In particular, trigger algorithms, lepton selections and b-tagging algorithms were optimized, the last again relying on the excellent performance of silicon vertex detectors. Furthermore, the invariant mass resolution for reconstructing the hypothetical Higgs mass from two b-tagged jets was pushed to the ultimate performance. The best possible background rejection was achieved by extensive use of multi-variate techniques such as neural networks or boosted decision trees. With those machine-learning techniques the discrimination between signal and background events could be improved, exploiting and optimally combining as much as possible the measured event properties. Undoubtedly, the extensive experience gained with these techniques also influenced their widespread use later at the LHC. Finally, the results from many channels and from the two experiments were combined, in order to maximize the statistical power.

In 2001, projections were made \[28\], under the assumption that some significant improvements in performance, compared with Tevatron Run I, would be achieved. These projections predicted that, with 10 fb\(^{-1}\) of good data on tape for each experiment, the combined CDF/\( \phi \) results could provide evidence (a 3 s.d. effect) for Higgs production with a mass around 125 or around 165 GeV. Indeed, the required performance improvements were achieved during Run II, and, furthermore, exactly this amount of good-quality data was recorded by both experiments between 2001 and September 2011.

Figure 3 shows typical plots of the combined CDF/\( \phi \) results for a particular amount of analysed data; in this case, \( 2 - 5.5 \text{ fb}^{-1} \), as presented in April 2008 \[29\] and November 2009 \[30\], the latter just at the start of LHC operations. They show the 95% confidence level upper limit on the Higgs production cross section, relative to the SM prediction, as a function of the hypothetical Higgs mass. That is, if the observed limit (the black line in the graphs) is at or below 1 for a given Higgs mass range, then the production of a Higgs boson, as predicted by the SM, is excluded at the 95% confidence level for those masses. The dashed line indicates the expected limit, obtained
for the first time. Later on, this excluded range was extended to $149 < M < 166$ GeV. Experiments at the LHC were already able to claim discovery (5 s.d. effect) for a Higgs boson of mass around 125 GeV. However, by the time this excess turned out to be significant, the interestingly, an excess at the level of three standard deviations was finally observed in the mass centre-of-mass energy corresponding to the mass of the $Z$ boson of approximately 0.1 GeV/c$^2$; the W boson mass has been determined from LEP and Tevatron data to a relative uncertainty of about 0.1%.\cite{4}

Expanding in the coupling parameter(s), such as the fine-structure constant, is performed up to a certain order. Figure 4 shows an example of such an expansion, for the calculation of the expected upper limit on the Higgs cross section relative to its SM prediction should move closer and closer to the horizontal black line at 1. Thus, the evolution of this plot over the years can be likened to the scene of a curtain falling on a stage, with the show being over for a particular Higgs mass hypothesis when the line at 1 is crossed. Indeed, during the first years of Run II, the accumulated data were not yet sufficient to exclude any range of Higgs masses. However, by November 2009, as shown in figure 3b, a small range, $163 < M_H < 166$ GeV, could be excluded for the first time. Later on, this excluded range was extended to $149 < M_H < 182$ GeV.\cite{5} More interestingly, an excess at the level of three standard deviations was finally observed in the mass range between 115 and 140 GeV. However, by the time this excess turned out to be significant, the experiments at the LHC were already able to claim discovery (5 s.d. effect) for a Higgs boson of mass around 125 GeV.

6. Indirect constraints from precision measurements sensitive to quantum loop effects

A completely different approach to the quest for the Higgs boson consisted in exploiting (i) highly sophisticated quantum field theory methods for calculating higher order quantum loop effects in perturbation theory and (ii) very precise measurements of SM observables, mostly obtained by the LEP and Tevatron experiments. To give a few examples, and to gauge what precision means in this context, the mass of the $Z$ boson has been measured with a relative uncertainty $\Delta M_Z/M_Z$ of 0.02%;\cite{4} the cross section for $e^+e^-$ annihilation into a $Z$ boson with subsequent hadronic decay, at a centre-of-energy corresponding to the $Z$ mass, is known with a relative uncertainty of about 1%;\cite{5} the $W$ boson mass has been determined from LEP and Tevatron data to a relative uncertainty of approximately 0.1%; and the mass of the top quark is known to better than 1%.\cite{4}

Theoretical predictions for such observables are obtained by perturbative methods, where an expansion in the coupling parameter(s), such as the fine-structure constant, is performed up to a certain order. Figure 4 shows an example of such an expansion, for the calculation of the

\footnote{See pdg.lbl.gov for up-to-date compilations of such measurements.}
matrix-element squared corresponding to the cross section for $e^+e^-$ annihilation into a fermion–antifermion pair. Only a few representative Feynman diagrams are shown here. Beyond the leading order term, quantum loop corrections start to appear. These can involve (virtual) particles, such as top quarks or a Higgs boson, which might be too heavy to be produced as real particles in some final state of the $e^+e^-$ interaction, but which lead to calculable and eventually measurable corrections to the leading order predictions. For example, the top–anti-top quark loop shown in the centre of figure 4 gives corrections proportional to the square of the top quark mass, while quantum loops involving a Higgs boson, such as the third term of the expansion in figure 4, depend logarithmically on the Higgs mass. That is, corrections sensitive to the top quark mass are at the per cent level, while those sensitive to the Higgs mass are smaller, below a per cent. If theoretical predictions, which include such corrections as a function of the top and Higgs boson masses, are compared with measurements with precision at the per mille level, we expect to obtain constraints on these mass parameters, without having to directly produce the particles of interest.

A proof of principle for this indirect probing of heavy particles was given throughout the 1990s. The early LEP data, mostly on $Z$ boson properties, were sensitive to the large top-loop corrections. With ever increasing precision of the data from the LEP1 run, the prediction of the possible mass range for the not-yet discovered top quark improved throughout the years, as shown in figure 5 as a coloured band. By the time of the direct top quark discovery at the Tevatron, the estimated top quark mass was around 170 GeV with an uncertainty of about 20 GeV, perfectly consistent with the reconstructed mass of the directly discovered top quark.

Figure 4. Schematic representation of the perturbative expansion for calculating the squared matrix element of the cross section for $e^+e^-$ annihilation into a fermion–antifermion pair; representative higher order diagrams involving quantum loops with top quarks and a Higgs boson are indicated. (Online version in colour.)

Figure 5. Comparison of indirect constraints from LEP data (coloured band) and the directly reconstructed top quark mass from the Tevatron experiments, as a function of time [32].
This success of the quantum loop and precision data approach gave confidence that the method could be extended in order to also obtain constraints on the Higgs boson mass. Indeed, such a programme of comparing a large set of precise data with SM predictions was carried out throughout the decade before the start of LHC operations. In addition to the $Z$ boson observables obtained at LEP1, this approach strongly profited from precise determinations of the $W$ boson mass at LEP2 and the Tevatron, and the ever increasing precision on the top quark mass measured by CDF and DØ. As an example, figure 6a shows the result of a fit to the complete set of observables, with only the unknown Higgs mass parameter left as the floating variable in the fit [32]. The blue band with the central black line is a measure of the overall fit quality, with a minimum (best fit) obtained for a Higgs mass of $129^{+74}_{-49}$ GeV. At the same time, this fit can be used to determine an upper limit (at the 95% confidence level) on the Higgs mass of 285 GeV. Taking the results as summarized by the PDG (pdg.lbl.gov), in figure 6b the best-fit result and the upper limit on the Higgs mass are displayed as they developed over the years. Very clearly, these analyses predicted the existence of a Higgs boson with mass not much larger than the direct lower limit obtained at LEP, assuming the validity of the SM. The fact that the recently discovered Higgs boson turned out to have a mass consistent with these indirect constraints again represents a triumph for the SM as a field theory, which correctly describes our available measurements of elementary particle properties. It should be mentioned that a plethora of similar indirect constraints and predictions was produced over the years, by typically extending the overall theoretical context beyond the SM; for example, carrying out such a programme of fitting in the context of a supersymmetric extension of the SM. An impressive compilation of more than 100 indirect Higgs mass predictions can be found in [33].

7. Summary

I have made an attempt to give a brief historical overview of the experimental efforts to search for the Higgs boson, prior to the finally successful experiments at the LHC. I have indicated how the permitted Higgs mass range was more and more constrained and narrowed down over recent decades, thanks to direct searches at LEP and the Tevatron, and also thanks to global fits of SM predictions to a large set of precisely measured parameters, such as the masses of the $W$ boson and the top quark. At the start of LHC operations, there were strong indications that the Higgs boson
should be rather light, i.e. have a mass in the range of 114–150 GeV, roughly speaking; a range within which it was discovered by the LHC experiments in 2012. During this long quest, there have been many experimental and theoretical advancements, which also influenced the design of the LHC experiments and the LHC data analysis techniques. I have tried to highlight some of those developments. Last but not least, it should not be forgotten that all these experimental successes would not have been possible without the excellent performance of the accelerators, thanks to the dedication and achievements of the involved personnel.

Acknowledgements. I express my gratitude to the organizers of this event at the Royal Society in London, for their invitation and their hospitality. I would also like to thank my colleagues, who have helped me during the preparation of the talk and this review, in particular D. Treille, F. Pauss, B. Kilminster and J. Virdee.

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