Chapter 15

The Higgs Boson Search and Discovery

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We present a brief account of the search for the Higgs boson at the three major colliders that have operated over the last three decades: LEP, the Tevatron, and the LHC. The experimental challenges encountered stemmed from the distinct event phenomenology as determined by the colliders energy and the possible values for the Higgs boson mass, and from the capability of these colliders to deliver as much collision data as possible to fully explore the mass spectrum within their reach. Focusing more on the hadron collider searches during the last decade, we discuss how the search for the Higgs boson was advanced through mastering the experimental signatures of standard theory backgrounds, through the comprehensive utilization of the features of the detectors involved in the searches, and by means of advanced data analysis techniques. The search culminated in 2012 with the discovery, by the ATLAS and CMS collaborations, of a Higgs-like particle with mass close to 125 GeV, confirmed more recently to have properties consistent with those expected from the standard theory Higgs boson.

1. Overview

Ever since the seminal papers by Englert, Brout, Higgs, Guralnik, Hagen, and Kibble appeared in 1964,¹ the search for the Higgs boson, a neutral scalar particle of unknown mass, m_H , has preoccupied several generations of experimentalists. A publication, in 1976, outlining the phenomenological profile of the Higgs boson² described the lower bounds on m_H that existed at the time (18 MeV), coming mainly from analysis of star emissions and from neutron scattering experiments. It also showed that masses of up to 4 GeV could be accessible in “high-energy” hadron colliders (Fig. 1(a)). In that publication, the decay branching fractions for Higgs boson masses up to 100 GeV were presented (see Fig. 1(b)). It is interesting to notice the many particles (which we now know exist, and into which the Higgs boson can actually decay) that are missing from the picture, and to compare it with the current picture shown in Fig. 2. In that publication a couple of

(a)

(b)

Fig. 1. (a) Higgs boson limits as a function of m_H in 1976. (b) Higgs boson branching ratios as expected in 1975.

whimsical statements were made: (i) “The situation with regard to the Higgs boson is unsatisfactory. First it should be stressed that they may well not exist...”, and, at its conclusion, (ii) “We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm 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.”

Fig. 2. Higgs boson branching ratios as expected in 2012.

As it happened, things played out somewhat differently. And, notwithstanding that message, after the discovery of the W and Z bosons at CERN in 1983, the attention to the search for the Higgs boson gained significant momentum. This quest was also spurred by several writings on the topic, amongst them was the “*The Higgs Hunter Guide*” book,³ published in 1990, which contained an exhaustive account of the phenomenology of the Higgs boson at lepton and hadron colliders. In fact, the Higgs boson search was very much on the menu of the experiments at the *Large Electron Positron* (LEP) collider at CERN,^{4,5} and front and center in the program of the ill-fated *Superconducting Super Collider* (SSC) in the United States.

During the LEP1 era (1989–1995), the e^+e^- center-of-mass collision energy, $\sqrt{s}$, was in the 89–93 GeV range, around the Z boson mass. During the LEP2 era (1996–2000) the collision energy increased above the W -pair production threshold of 160 GeV, and up to a maximum of 209 GeV. Amongst their many achievements, the four LEP experiments: Aleph, Delphi, L3, and Opal, all collaborations made up of hundreds of physicists, determined that there are exactly three types of (light) neutrinos.

Since the beginning the LEP experiments diligently searched for direct evidence for the Higgs boson, setting lower limits on its possible mass along the way. As shown in Fig. 3(a), at LEP the SM Higgs boson was mainly produced through Higgs-strahlung in the s -channel, $e^+e^- \rightarrow HZ$,^{6,7} where the Z boson in the final state is either virtual (LEP1), or on-shell (LEP2). The SM Higgs boson could also be produced by WW and ZZ fusion in the t -channel,⁸ but these processes have small cross sections and would have contributed minimally to the sensitivity, therefore no dedicated searches for these processes were performed. The sensitivity of the LEP searches to the Higgs boson strongly depended on the center-of-mass energy, E_{CM} . For $m_H < E_{\text{CM}} - m_Z$, the cross section is of order 1 pb or more, while for

Fig. 3. (a) Higgs boson production cross sections at LEP compared to WW , ZZ and fermion–antifermion cross sections. (b) CL_s values as function of m_H for data and expectations from the signal + background hypothesis and background-only hypothesis with 68% and 95% CL error bands.

$m_H > E_{\text{CM}} - m_Z$, the cross section is smaller by at least an order of magnitude. However, in practice, LEP did not have sensitivity for $m_H > E_{\text{CM}} - m_Z$.

At LEP2 searches were performed in four different channels: (i) the four-jet channel $ZH \rightarrow q\bar{q}, q\bar{q}$ (which included specific analysis for $ZH \rightarrow q\bar{q}, b\bar{b}$), (ii) the missing-energy channel $ZH \rightarrow \nu\bar{\nu}, q\bar{q}$ (including $ZH \rightarrow \nu\bar{\nu}, b\bar{b}$), (iii) the tau channels $ZH \rightarrow q\bar{q}, \tau^+\tau^-$ and $ZH \rightarrow \tau^+\tau^-, q\bar{q}$ (including $ZH \rightarrow \tau^+\tau^-, b\bar{b}$), and (iv) the lepton channels $ZH \rightarrow e^+e^-q\bar{q}$ and $ZH \rightarrow \mu^+\mu^-, q\bar{q}$ (with $ZH \rightarrow e^+e^-, b\bar{b}$ and $ZH \rightarrow \mu^+\mu^-, b\bar{b}$). At each of the LEP experiments, the different production and decay modes were analyzed separately and the data recorded at each center-of-mass energy were studied independently. The results from the four LEP experiments were then combined.

With all data in hand, strong upper bounds on the $e^+e^- \rightarrow ZH$ cross section were obtained for Higgs boson masses between 1 keV and $\simeq 115$ GeV. The final combination of the LEP data yielded a 95% C.L. lower bound of 114.4 GeV for the mass of the SM Higgs boson.⁹ The median limit expected in a large ensemble of identical experiments when no signal is present was 115.3 GeV, and was limited by the collision energy achieved by the accelerator. Figure 3(b) shows these results. It was not possible to push the collider energy further and, to the disappointment of many, in particular since there was a small excess around a mass of ~ 115 GeV,

LEP was shut down at the end of the year 2000. A short account of the progression and excitement of the enterprise can be found in Ref. 10.

The SSC, on the other hand, never got to take any data. The accelerator would have collided protons in a ring of 87 kilometers in circumference at a center-of-mass energy of 40 TeV. However, the project was plagued by cost overruns and managerial issues, all during a rough political period in the U.S.^{11,12} After initial construction, cancelation ensued in 1993. It was a turning point for High Energy Physics in the U.S. and an opportunity for Europe to pursue at full steam the construction of the Large Hadron Collider (LHC) in the LEP tunnel.

Between the shutdown of LEP and the advent of the LHC the Tevatron experiments, CDF and D0, had the playing field to themselves in the search for the Higgs boson. The Tevatron was a proton–antiproton collider configured to collide beams of 36 bunches at a center-of-mass energy of 1.96 TeV.

The value of the Higgs boson mass was not specified by theory. However, electroweak radiative corrections are sensitive to the mass of the particles that may play a role in them, and therefore the consistency between different electroweak measurements can constrain the values of those masses. Before the discovery of the top quark at the Tevatron¹³ in 1995, which was another epic search saga in itself, the value of the Higgs boson mass was not very constrained experimentally either. The precision measurements of the top-quark and W -boson masses that were made throughout the Tevatron program considerably narrowed the range for the possible value of the Higgs boson mass. The Higgs boson contributes to the observed W and Z gauge boson masses through loop diagrams, leading to a logarithmic dependence of the ratio of the W and Z masses on the Higgs boson mass. The top quark contributes to the observed W boson mass through loop effects that depend quadratically on the top mass. A global fit to precision electroweak data at the time of the Higgs boson discovery (accumulated over the last two decades mainly at LEP, SLC and

Fig. 4. Constraints from the top quark mass, the W boson mass and other SM measurements compared to the allowed Higgs search range in March 2012.

the Tevatron), obtained that $m_H = 94^{+29}_{-24}$ GeV, or $m_H < 152$ GeV at 95% C.L.¹⁴ The measurements of the top-quark mass and of the W boson mass used in these fits were 173.2 ± 0.9 GeV,¹⁵ and 80.385 ± 0.015 GeV,¹⁶ respectively. Figure 4 shows the constraints to the Higgs boson mass value from these measurements as they stood in March 2012, while they were weaker when the Run II of the Tevatron started in 2002.

In the year 2000 a working group explored the possibilities for discovery of the Higgs boson at the Tevatron,¹⁷ concluding the following:

“Based on a simple detector simulation, we have determined the integrated luminosity necessary to discover the SM Higgs in the mass range 100–190 GeV. The first phase of the Run 2 Higgs search, with a total integrated luminosity of 2 fb^{-1} per detector, will provide a 95% CL exclusion sensitivity comparable to that expected at the end of the LEP2 run. With 10 fb^{-1} per detector, this exclusion will extend up to Higgs masses of 180 GeV, and a tantalizing 3-sigma effect will be visible if the Higgs mass lies below 125 GeV. With 25 fb^{-1} of integrated luminosity per detector, evidence for SM Higgs production at the 3-sigma level is possible for Higgs masses up to 180 GeV. However, the discovery reach is much less impressive for achieving a 5-sigma Higgs boson signal. Even with 30 fb^{-1} per detector, only Higgs bosons with masses up to about 130 GeV can be detected with 5-sigma significance.” Figure 5(a) shows graphically these results.

Key to the success of the Tevatron’s Higgs search program was the capacity of the accelerator to deliver ever more intense proton and antiproton beams. Through tremendous effort and inventiveness, the instantaneous luminosity was increased about one order of magnitude with respect to its maximum during Run 1, when the top quark discovery was made. Figure 5(b) shows the instantaneous luminosity delivered by the Tevatron over its 25 years of lifetime, reaching a maximum of $4 \times 10^{32} \text{ cm}^2 \text{ s}^{-1}$ by the time it shut down. Tevatron operations focused not only on records for maximum instantaneous luminosity but also on maximizing the integrated luminosity delivered. As the luminosity improved, the mission to search for the Higgs boson ultimately became the main driver of the Tevatron’s Run 2 program, which lasted from 2001 until 2011.

An important aspect in the search of the Higgs boson at the Tevatron was the continuous interplay of cooperation and healthy competition between the CDF and D0 collaborations. It was clear from the start that combining their datasets would ultimately give the Tevatron the best chance for signal sensitivity in the widest range of Higgs boson masses. At the same time, each experiment strived in besting each other in sensitivity by implementing innovative analysis techniques and incorporating as many channels as possible into the search. This led to a cross-pollination with the result that each experiment truly maximized its potential. A Tevatron Higgs Working Group was established in 2006 with the goal of combining the results from the two experiments, sharing discussions on the proper treatment of uncertainties, both experimental and theoretical, and on statistical methods for

(a)

(b)

Fig. 5. (a) The integrated luminosity required per experiment as estimated in 2000, to either exclude a SM Higgs boson at 95% CL (curve at the bottom) or discover it at the 3-sigma (curve in the middle) or 5-sigma level (curve at the top), as a function of the Higgs mass. These projections were based on the Higgs production cross sections available at that time, sometimes based on Leading Order calculations only. (b) Instantaneous luminosity at the Tevatron collider over its 25 years of operation.

the combination. In fact, as time went on, the sensitivity of the searches improved far more than what was expected from increased luminosity alone.

At the end of Run 2 each of the Tevatron experiments collected datasets corresponding to a total integrated luminosity of 10 fb^{-1} . And for the first time since the

final LEP limits were reported, new direct constraints were made on the mass of the Higgs boson, excluding the 156–177 GeV mass range.¹⁸ With time the exclusion window in this “high-mass” region, dominated by the $H \rightarrow WW$ channel, was extended.¹⁹ Had the Higgs boson mass been in this range, the discovery story would have been very different! These results, in combination with the precision electroweak measurements were able to establish, before the LHC produced significant results, that a SM Higgs boson with mass above $\simeq 145$ GeV was excluded at 95% C.L.²⁰ In the remaining window at the lower mass range, dominated by the $H \rightarrow b\bar{b}$ channel, and where the sensitivity was actually worse, and not better as predicted by the 2000 Higgs Working Group, the Tevatron experiments could ultimately not exclude the presence of a Higgs boson. In July 2012, an excess of events, at a mass consistent with 125 GeV, corresponding to a significance near 3 standard deviations, was reported.²¹ As it was, to reach much higher sensitivity in the lower mass range the experiments would have had to integrate several times more luminosity through an extended run. Much consideration was given to this idea, however, with the advent of the LHC this possibility did not materialize. Still, due to the difficulty to unequivocally observe the $H \rightarrow b\bar{b}$ channel at the LHC, until considerably more data is accumulated in the 13 TeV run, the contributions of the Tevatron to the Higgs search and discovery were timely and significant.

The Lausanne Workshop in 1984²² can be considered as the event that gave birth to the LHC, although its actual construction started only in 1998. An interesting account of the construction and commissioning of the LHC can be found in Ref. 23. The goal was to discover a Higgs boson with a mass anywhere in the 0.1 to 1 TeV range, which is where it was theoretically expected. With that in mind, the LHC was built to collide protons at a center-of-mass energy of $\sqrt{s} = 14$ TeV with a nominal instantaneous luminosity of $L = 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and a bunch spacing of 25 ns. It can also collide heavy ions. Four main experiments were installed around the ring: two general-purpose detectors, ATLAS²⁴ and CMS²⁵ a detector dedicated to study heavy flavor physics, LHCb,²⁶ and a detector dedicated to the study of heavy ion collisions, ALICE.²⁷

At hadron colliders the Higgs boson can be produced through several processes that are initiated either by quark–antiquark annihilation or by gluon–gluon fusion. Figure 6 shows these processes. Due to its higher energy relative to the Tevatron, the LHC, at 7 TeV for example, would produce particles with masses of 100 GeV at a rate of about 4 times higher for quark–antiquark induced processes, and at a rate of about 20 times higher for gluon–gluon processes. This is shown in Fig. 7. However, given that the cross sections for all background processes also increase with the increasing energy, this did not make the search for the Higgs boson at the LHC much easier. Figure 8 shows the Higgs production cross section being several orders of magnitude smaller than those of important standard theory background processes.

Fig. 6. Higgs production processes at hadron colliders.

Fig. 7. Ratios of parton luminosities at 7 TeV LHC and at the Tevatron.

Fig. 8. Cross sections vs energy for different processes.

On September 10th, 2008, the LHC began the final preparations towards operation but unfortunately soon after an electrical fault with the interconnection between two dipole magnets caused a Helium explosion that damaged a large section of the accelerator.²⁸ It took more than a year to repair the damage, understand the problem, and establish proper measures to avoid recurrence. It was decided to limit the current to the magnets, which in turn limited the beams energy to 7 TeV, until the connections between all magnets could be fixed properly in a future long shutdown period. Meanwhile during 2010 and 2011 (Run 1) protons collided at that energy, and a total of 5.6 fb^{-1} integrated luminosity was delivered. In 2012 the energy was safely increased to 8 TeV, and a total of 23.3 fb^{-1} integrated luminosity was delivered. Figures 9 and 10 show the peak instantaneous luminosity and the cumulative integrated luminosity for both the 7 and 8 TeV running periods. The peak instantaneous luminosity that was ultimately reached was about $7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

Fig. 9. LHC instantaneous luminosities as recorded by the ATLAS experiment in 2010, 2011 and 2012.

Fig. 10. LHC integrated luminosities as recorded by the ATLAS experiment in 2012.

At the LHC the search for the Higgs boson proceeded in parallel with the ATLAS and CMS experiments competing with each other to reach better sensitivity. Notwithstanding the Tevatron results, the LHC experiments approached the search without any *a priori* bias on the value of the Higgs boson mass and all possible channels were addressed. As detailed in Sec. 3, at high masses the sensitivity was dominated by the $H \rightarrow ZZ$ and $H \rightarrow W^+W^-$ channels while at the lower masses, near 125 GeV, the $H \rightarrow \gamma\gamma$ and the $H \rightarrow ZZ^{(*)} \rightarrow llll$ dominated the sensitivity.

By August 2011, with an integrated luminosity of about 2 fb^{-1} (ATLAS) and 1.5 fb^{-1} (CMS), the mass range of 145–450 GeV was excluded,²⁹ surpassing for the first time the Tevatron results. First small excesses were seen in July, but diminished

in August. In December 2011, with about 5 fb^{-1} of data collected at $\sqrt{s} = 7 \text{ TeV}$ the following mass ranges were excluded^{30,31} at the 95% CL by either ATLAS or CMS: $110.0 < m_H < 117.5$, $118.5 < m_H < 122.5$, and $127.5 < m_H < 600$. A small excess, with a local significance of $\sim 2.5\sigma$, was observed by both experiments at a mass of about 125 GeV, fueling much speculation that a discovery was in the cards. In the following Winter conferences (March 2012) the Tevatron reported an excess of similar strength in a wider but compatible mass region. The excess was coming mainly from the associated production channel, with the Higgs boson decaying to a pair of b quarks, which was not observable at that time by the LHC experiments.

On July 4th, 2012, the search for the Higgs boson culminated with the announcement that ATLAS and CMS had independently discovered a new particle with mass close to 125 GeV.^{32–34} The discovery was clear, the signal being seen in several channels with high statistical significance, for a combined significance of 5σ or more by both experiments independently. CDF and D0 then released their combination on the full Tevatron dataset showing evidence for the decay in $b\bar{b}$ of a particle compatible with the one discovered at CERN.²¹ The data gathered at the LHC in the months that followed helped strengthen the signals found and allowed for the first measurements of various properties of the new particle to be made. An account of these measurements can be found in a dedicated Chapter in this book.

In March 2013 the LHC entered a shutdown period planned for machine maintenance and to perform the needed interventions to bring the beams to collide at a center-of-mass energy of 13 TeV, close to the original design. At the time of this writing the first collisions at this new record energy were recorded, bringing great expectations for new discoveries.

In the following sections we discuss in more detail, both for the Tevatron and the LHC, the factors that contributed to the search and discovery of the Higgs boson, and the results obtained at the time of the discovery.

2. Higgs Searches at the Tevatron

While the Run 1 of the Tevatron (1992–95) had not enough luminosity to search for the SM Higgs boson, the luminosity gain expected in Run 2 changed the situation completely, allowing for the Higgs boson search to become a major physics goal of the CDF and D0 experiments. However, as mentioned earlier, it was clear from the beginning that new advances in reconstruction, analysis and combination would be needed to have a chance to detect the Higgs boson. Before describing the paths followed, let us briefly remind the properties of these two experiments, while referring to Refs. 35 and 36 for the detailed characteristics of the CDF and D0 detectors.

The D0 tracking system was contained within a solenoidal magnet with a 2T field and consisted of an inner silicon micro-strip tracker surrounded by an outer

central scintillating fiber tracker. Track momentum measurements were made up to $|\eta| \sim 2.5$. Liquid argon calorimeters reach up to $|\eta| = 4.2$ and were used for the identification and energy measurement of electrons, photons, and jets. Muon detectors covered up to $|\eta| < 2$, and a 1.8 T toroidal magnet made it possible to determine muon momenta within the muon system alone.

The CDF tracking system consisted of a silicon micro-strip tracker surrounded by an open-cell drift chamber, all immersed in a 1.4 T solenoidal magnetic field. Tracking coverage extended up to $|\eta| \sim 2.0$. The sampling-scintillator calorimeters that surround the tracking system covered the pseudorapidity region of $|\eta| < 3.64$ and were based on a projective tower geometry. They used lead and iron as absorbers in the electromagnetic and hadronic modules, respectively.

At low masses ($m_H < 135$ GeV), the dominant decay of the Higgs boson is $H \rightarrow b\bar{b}$, but the search for direct ($gg \rightarrow H$) Higgs boson production in this decay mode, was not performed due to overwhelming multijet background. However, $q\bar{q}$ annihilation results in associated vector boson-Higgs boson production (VH) in $p\bar{p}$ collisions with a better signal to background ratio than available at a pp collider. The “primary” channels for searching for a low mass Higgs boson at the Tevatron, WH and ZH production, are best studied in the $\ell\nu b\bar{b}$, $\ell\ell b\bar{b}$ or $\nu\nu b\bar{b}$ final states. The lower branching ratios or poor signal to background of the other decay modes rendered their sensitivity smaller than these primary channels. They were also searched for to provide additional sensitivity in the combination of all channels, but are not described here, see for instance Ref. 37 for more details. In all the analyses, the data were separated into multiple orthogonal search samples of varying sensitivities.

Vector boson fusion production, associated production with vector bosons and direct Higgs boson production can also be exploited when the Higgs boson decays to a $\tau\tau$ pair, by making use of the kinematics of the potential additional jets in the final state. These processes suffer from significant background and so were considered as secondary channels at the Tevatron. Another secondary channel which was exploited at the Tevatron is the inclusive production of a Higgs boson with Higgs boson decay to two photons. The sensitivity of this channel is low due to the small branching ratio of this decay, typically smaller than 0.2%. The $t\bar{t}H$ production was also searched for, but has lower sensitivity.

Since the low mass analyses used advanced multi-variate techniques for separating signal and backgrounds and were obtained from low signal-to-background search samples, a crucial test was performed considering WZ and ZZ diboson production with Z decays to heavy flavor as signal, mimicking the final state of WH and ZH including the essential feature of resonant dijet production. These analyses, and their combination, were performed in the same way as their Higgs counterparts. The CDF + D0 combination displayed strong evidence (4.6σ) for such production, with a measured cross section $\sigma(VZ) = 4.47 \pm 0.97$ pb consistent with the SM prediction.³⁸

2.1. Low mass Higgs boson searches

The search for the processes $q\bar{q} \rightarrow VH + X$ in which a quark–antiquark pair leads to the production of the Higgs boson in association with a Vector boson (W or Z) was based on a total integrated luminosity $\mathcal{L} \simeq 10 \text{ fb}^{-1}$ of collision data collected by both the CDF and D0 detectors at the Fermilab Tevatron $p\bar{p}$ collider between 2002 and 2011. In the WH channel, candidate W boson events were preselected via their decays to an electron or a muon plus a neutrino ($W \rightarrow e$ or $\mu\nu$) while the Higgs boson was identified through its decay mode into a pair of b -quarks ($H \rightarrow b\bar{b}$).^{39,40} The experimental signature was a single isolated lepton, missing transverse energy, and either two or three (to accommodate additional gluon radiation in the hard collision) jets, at least one of which was required to be consistent with having been initiated by a b -quark.

To increase signal acceptance, the lepton identification criteria were as loose as possible. This resulted in backgrounds originating from multijet (MJ) events, in which one of the jets is misidentified as an isolated lepton. In CDF, the MJ background was strongly reduced by kinematic cuts and by using a dedicated multivariate technique to reject this background.³⁹ The remaining MJ background contribution was modeled from the data using side-band techniques. In D0, the MJ background contributions passing the preselection criteria in each sample was determined from the data using an unbinned matrix method approach.⁴⁰ The “physics” backgrounds with similar event topologies were modeled using Monte Carlo event generators. The SM predictions were used to set the relative normalizations of all the generated samples, with additional normalization factors applied to samples of $W + n$ partons generated using the ALPGEN Monte Carlo event generator. These factors were determined from data at the preselection stage where the SM Higgs boson contribution was negligible. The predicted backgrounds modeled the data well in the high statistics sample before a b -tagging algorithm was applied.

The analyses proceeded by subdividing the selected sample into orthogonal subsamples based on how many of the jets in the event, one or two, are consistent with having been initiated by a heavy b -quark, and at what level (“loose” or “tight”) of confidence, resulting in 6 (D0) or 7 (CDF) independent samples. In two b -tagged jet events, the dominant remaining backgrounds were from $Wb\bar{b}$, $t\bar{t}$, and single top quark production. In single b -tagged jet events the dominant backgrounds were W + light or c -quark jet production as well as MJ background events. To further discriminate the remaining backgrounds from the signal, MVA techniques were applied to each subsample.

The systematic uncertainties taken into account affected not only the normalization of the signal and backgrounds, but also the shape of the MVA output distributions. Uncertainties in the efficiencies of selection, on jet calibration and on the b -tagging criteria affecting the precision at which the background modeling is known were considered. The uncertainties on the parton density functions and the effect of

renormalization and factorization scales on signal and background simulation were also taken into account.

In the leptonic ZH channel, candidate Z boson events were preselected via their decays into e^+e^- or $\mu^+\mu^-$ pairs, and the associated Higgs boson was identified through its decay into a pair of heavy b -quarks ($H \rightarrow b\bar{b}$).^{41,42} Candidate events were required to have two or three jets, at least one of which was identified as a b -jet. In this final state, which required two leptons, the MJ background was negligible. The “physics” backgrounds were modeled using the same Monte Carlo event generators used in the WH analysis.

To maximize the lepton acceptance and benefit from higher quality lepton categories, the events were classified according to the lepton types. Those having both leptons identified with high confidence were treated separately from the others which contain loosely identified, forward, or track-based leptons. These samples were analyzed independently, allowing for an optimal sensitivity of the search. In addition, multivariate lepton selections were used. In CDF, to enhance the discriminating power of the dijet invariant mass, a neural network (NN) derived energy correction was applied to the jets. This correction depends on the missing transverse energy and its orientation with respect to the jets. In D0, jet energy resolution improvements were obtained through a kinematic fit of the complete event, since all particles can be detected in this process. These analyses also proceeded by subdividing the selected sample into 6 (D0) or 8 (CDF) orthogonal subsamples based on the number and the quality of the b -tagged jets in the event. CDF employed two NNs to simultaneously separate signal events from the dominant $Z + \text{jets}$ and kinematically different $t\bar{t}$ backgrounds. In single and double b -tagged jet events, the dominant remaining background was $Zb\bar{b}$. To suppress the remaining background MVA techniques were applied to each subsample. Systematic uncertainties were overall less important than for WH since no missing transverse energy was involved, but most of the other systematic uncertainties were of similar magnitude to those of the WH analyses.

The remaining $b\bar{b}$ analysis was built to detect the $ZH \rightarrow \nu\nu b\bar{b}$ process but was also sensitive to WH events in which the charged lepton was not identified, hence its alternate label as $VH \rightarrow \cancel{E}_T b\bar{b}$.^{43,44} Since this final state contains no leptons, triggering on these events and modeling the effects of the trigger requirements on the event selection were significant challenges. The triggers were based on $\cancel{E}_T$, with or without accompanying jets. The analyses were performed while studying in parallel several control samples to monitor the understanding of the background. Events were required to have significant $\cancel{E}_T$ and two or three jets, well separated from the $\cancel{E}_T$ direction. For the preselection, multivariate approaches were also applied to the events to remove a large part of the MJ background. For the final selection b -tagging was employed. For this analysis, the preselection plays a crucial role, given the size of the MJ background. As for the other $b\bar{b}$ analyses, the “physics” backgrounds were taken into account using Monte Carlo event generators. The preselected samples were subdivided into 6 (CDF) or 2 (D0) orthogonal subsamples based on the

Fig. 11. Distribution of the NN discriminant in the CDF $\cancel{E}_T bb$ analysis for the sample with two or three jets where two of the jets are tagged as b -jets by the secondary vertex algorithm. The data are well described by the sum of all the SM backgrounds. The simulated signal is also represented.

number and the quality of the b -tagged jets in the event. To suppress the remaining backgrounds multivariate discriminant techniques were applied to each subsample as shown in Fig. 11.

The results of CDF and D0 are presented here separately while the CDF + D0 combination is given in Section 4. The statistical techniques used are also described in Section 4. They allow for the extraction of the limit on the signal cross section normalized to the SM expectation, or, in case of excess, determine the p -value of the background fluctuation. At the lowest searches masses, when combining the three $H \rightarrow b\bar{b}$ topologies, CDF and D0 exclude at 95% C.L. Higgs bosons with masses smaller than 96 GeV and 102 GeV, respectively. However, in the results from both collaborations an observed limit above the background-only expectation was obtained for the $\simeq 120$ –140 GeV range. The local p -values were calculated and found to be minimal for a Higgs boson mass of 135 GeV at CDF⁴⁵ and D0⁴⁶ searches, where the local significance of these deviations with respect to the background-only hypothesis corresponded to 2.5 (1.5) σ global significances.

Higgs boson searches using tau leptons decaying hadronically (τ_h) complemented those using electrons and muons. CDF performed a generic analysis searching for Higgs bosons decaying to τ lepton pairs originating from direct $gg \rightarrow H$ production, associated WH or ZH production, and vector boson fusion production. The D0 $\ell\tau_h jj$ analyses also included direct $gg \rightarrow H$ production, associated WH or ZH production, and vector boson fusion production.⁴⁷ Decays of the Higgs boson to tau, W , and Z boson pairs were considered. A final state consisting of one leptonic τ decay, one hadronic tau decay, and two jets were required. Both CDF⁴⁸ and D0⁴⁹ also searched for Higgs bosons decaying into diphoton pairs with the full statistics

(10 fb⁻¹) but their sensitivities remained limited. The CDF analysis searches for a signal peak in the diphoton invariant mass spectrum above the smooth background originating from QCD production in several detector based categories with different signal to background ratios. In the D0 analysis the contribution of jets misidentified as photons was reduced by combining information sensitive to differences in the energy deposition from real or false photons in the tracker and in the calorimeter in a neural network output (NN_o). The $t\bar{t}H$ production is interesting for the direct tH coupling it involves, however its cross section was too small at the Tevatron to contribute to the overall search sensitivity.

2.2. High mass Higgs boson searches

The SM Higgs boson has a strong coupling to both massive electroweak bosons. For $m_H > 135$ GeV the decay to a pair of W bosons is dominant since even below the threshold to produce on-shell W bosons the decay rate to one real and one virtual W boson is substantial.

The $H \rightarrow W^+W^{-(*)}$ decay was searched in final states with at least one charged lepton and from all production processes with substantial cross section. In addition, searches for the sub-dominant decay $H \rightarrow ZZ$ were performed. The Tevatron experiments observed all of the direct diboson production processes with pairs of heavy gauge boson in final states that were topologically similar to those used in the Higgs boson search.

The diboson production analyses in final states with charged leptons were performed with the same techniques used in the high mass Higgs boson search, also providing measurements of the WW , WZ , and ZZ cross sections.^{50–54}

The Higgs analysis typically required a triggered lepton with $p_T > 20$ GeV, possibly additional leptons with lower thresholds, and significant $\cancel{E}_T$ that was not aligned along the direction of other physics objects in the events. The events were then categorized into a large number of topologies that were consistent with various Higgs boson production and decay modes. These topologies were characterized by the number of charged leptons, whether the leptons were same or opposite charge, and the number of jets (n_j). Each topology involved a limited set of dominant signals and backgrounds allowing for optimal discrimination, and was therefore analyzed separately. The most sensitive analysis topology involving zero jets and leptonic $H \rightarrow W^+W^-$ is described below, while the subdominant modes are briefly discussed afterwards.

The signature for $ggH \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu} + n_j$ jet when $n_j = 0$ is two opposite sign leptons, $\cancel{E}_T$, and no observed jets.^{55,56} The signal in this final state was almost 100% produced by the ggH process. The dominant background was from SM direct WW production with minor contributions from Drell–Yan production, the WZ and ZZ diboson processes where one or more charged leptons were not detected, and $W + \text{jets}$ or $W + \gamma$ where a jet was misidentified as a lepton or the γ converts to an electron-positron pair, only one of which is detected. The strongest

discriminant was the opening angle between the leptons in two dimensions, $\Delta\phi$, or three dimensions, ΔR , due to the spin correlation between the two spin one W bosons when decaying from the scalar Higgs boson. The D0 experiment further subdivided this mode by lepton flavor. CDF subdivided this analysis into modes with two well identified leptons, or one well identified lepton plus an isolated track, and analyzes events with low dilepton invariant masses as a separate category. When $n_j = 1, 2$, the signature is two opposite sign leptons, $\cancel{E}_T$, and observed jets. These topologies had substantial contributions from VH or VBF where the jets were observed from either one of the vector boson decays or final state quarks respectively and additional background from top pair production.

Associated production $VH \rightarrow VW^+W^-$ was also studied in events with either same sign leptons or trileptons when the associated vector boson decays to charged leptons. The background included W + jets with a misidentified lepton in the same sign mode and SM direct WZ production in the trilepton case. Higgs boson production were also searched for inclusively in events where one of the W boson decays leptonically and the other W boson decays to two quark jets,⁵⁷ i.e. $(ggH, VH, VBF) \rightarrow H \rightarrow WW \rightarrow \ell\nu + \geq 2 \text{ jet}$. The dominant backgrounds were from W + jets and multijet background where a jet is misidentified as a lepton. The experiments also considered modes where one W boson decays to a τ lepton which decays hadronically. A search for the Higgs boson was also performed in the $H \rightarrow ZZ$ mode where both Z bosons decay to charged leptons.⁵⁸ The only significant background in this mode was SM direct ZZ production but the sensitivity remained low given the cross section times BF.

All these search channels would have selected a total of approximately 75 Higgs boson events per detector for $m_H = 165 \text{ GeV}$, with a good signal to background ratio using MVA discriminants as illustrated in Fig. 12. The largest discriminating power was coming from the spin correlation variable, due to the unique scalar nature of the Higgs boson. No significant excess was seen in these high mass searches and limits were thus extracted, taking into account systematic uncertainties. The experiments each achieved expected sensitivity within a factor of approximately 1.5 of the SM cross section, in a mass range from $m_H = 140\text{--}185 \text{ GeV}$. The CDF (D0) analysis excluded the SM Higgs boson in the mass range $m_H = 148\text{--}175 \text{ GeV}$ ($157\text{--}172 \text{ GeV}$).^{59,60} The CDF + D0 combined results are presented in Section 4.

3. Higgs Searches at the LHC

The search for the Higgs boson by the ATLAS and CMS experiments targeted from the start a very broad mass range. It was important to confirm the excluded range from the Tevatron experiments and to extend with direct searches the mass range to the highest accessible masses. It was paramount to explore the low mass window that had not been excluded by LEP or by the Tevatron. This meant that a large variety of processes needed to be studied. Figure 13(a) shows the cross sections for

Fig. 12. NN discriminant for $ggH \rightarrow WW \rightarrow \ell\nu\ell\nu + 0$ jet at CDF. The distribution for background and a $H \rightarrow WW$ signal with $m_H = 165$ GeV (multiplied by 10) are compared.

Fig. 13. (a) Higgs production cross sections at the LHC at $E_{cm} = 8$ TeV. (b) Standard Theory Higgs boson production cross section times branching ratio at $E_{cm} = 8$ TeV.

the various productions mechanisms for a Higgs boson at the LHC as a function of its mass at 8 TeV. The convolution of these cross sections with the possible decay modes results in many final states with very different yields depending on m_H , as exemplified in Fig. 13(b).

At large masses ($\simeq 200$ GeV) the searches were performed in channels where the Higgs is produced through gluon fusion and decays to ZZ or W^+W^- and, as seen in

the figure, included all channels in which at least one of the bosons decayed leptonically. These channels had the greatest sensitivity as, for the most part, they did not have to contend with the copious backgrounds that purely hadronic channels suffer from. At lower masses a wide variety of search channels were accessible from all production mechanisms: gluon-fusion (gg), vector-boson-fusion (VBF), and production in association with vector-bosons (VH) or top-quark pairs (ttH). In this mass range, and especially, at around 125 GeV the Higgs boson has many possible decays with significant branching fraction such that the various final states included essentially all possible detectable physics objects: leptons, photons, tau-leptons (taus), b quarks and generic jets.

Of course Fig. 13(b) by itself does not represent the actual sensitivity of each of the channels represented there as these are inclusive yields and triggering bandwidth and different event reconstruction efficiencies and background levels affect the sensitivities significantly. Before describing in more detail the channels studied and the data analysis challenges they represented, we describe in brief the characteristics of the multi-purpose ATLAS and CMS detectors that allowed the experimentalists to explore this large set of final states. The details of the design of these magnificent detectors is described in Ref. 24 and in Ref. 25.

The ATLAS detector includes an inner tracker that consists of a silicon pixel detector, a silicon micro-strip detector, and a transition radiation tracker. It is inside a solenoidal magnet with a 2 T field, and measures the trajectories of charged particles and in the $|\eta| < 2.5$ pseudorapidity range. The inner tracker is surrounded by a high-granularity liquid-argon sampling electromagnetic calorimeter which provides electron and photon identification in the $|\eta| \sim < 2.4$ range. An iron-scintillator tile calorimeter provides hadronic coverage in the central pseudorapidity range. The end-cap and forward regions extend the calorimetry coverage to $|\eta| < 4.9$, and both their electromagnetic and hadronic components are instrumented with liquid argon. The muon spectrometer covers the $|\eta| < 2.4$ range and surrounds the calorimeters. It consists of three large superconducting toroids, and a system of precision tracking chambers and specialized detectors for triggering.

The CMS detector comprises, in successive layers outwards from the collision region, a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, a brass/scintillator hadron calorimeter, a superconducting solenoid, and gas-ionization chambers embedded in the steel return yoke for the detection of muons. The silicon detector provides charged particle tracking in the pseudorapidity range of $|\eta| < 2.5$. The electromagnetic calorimeter and the muon chambers provide coverage to $|\eta| < 3$ and $|\eta| < 2.4$, for electron and muon identification, respectively. The return field of the magnet allows independent momentum measurement and triggering in the muon chambers. Jet finding can be performed up to an expanded pseudorapidity range of $|\eta| < 5.0$ using forward calorimeters.

These detectors need to overcome the challenges resulting from the high intensity proton beams that the LHC delivered. During Run 1 the LHC proton bunch spacing

Fig. 14. Luminosity-weighted distribution of the mean number of interaction per crossing.

Table 1. The five main decay channels in the low-mass Higgs boson search and discovery at the LHC.

Decay channel	Reconstructed mass resolution
$H \rightarrow \gamma\gamma$	1–2%
$H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$	1–2%
$H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell'^-\nu$	~20%
$H \rightarrow \tau^+\tau^-$	~15%
$H \rightarrow b\bar{b}$	~10%

was 50 ns and therefore proton–proton collision events occurred at a rate of approximately 20 MHz. Figure 9 shows the instantaneous luminosity during Run 1, which reached a peak of $7.7 \times 10^{37} \text{ cm}^2\text{s}^{-1}$ by 2012. As a consequence multiple proton–proton inelastic collisions occurred within a single bunch crossing. The cross section for inelastic proton–proton interactions is $\sigma \approx 60 \text{ mb}$, and the resulting multiplicity profile for these interactions (called “*pileup*”), as measured by the ATLAS detector, is shown in Fig. 14. At 8 TeV the average number of pileup collisions per event is about twenty, resulting in about 4×10^8 collisions per second seen by the detectors. The digitized information from each collision is about one Mbyte and recording 4×10^8 Mbytes/second over roughly 10^7 second of effective running during a year (roughly 30% of the time) would result in about 4 million Petabytes of data, and clearly impossible to record it all. To get to a manageable rate at which to record events, of a few hundred Hz, a multi-level triggering system is implemented. At each stage a decision is made on whether there might be a collision worth examining further until the event gets finally recorded. Still, even for interesting events, in order to maintain the trigger rates low enough, thresholds on all physics objects needed to be imposed at the trigger level resulting in acceptance losses. It was therefore imperative for ATLAS and CMS to maintained a so-called trigger menu that was optimized for the Higgs discovery, not an easy feat.

In what follows we describe the analyses as they were done at the time of the announcement of the Higgs boson discovery, including the figures with the available data at the time. We naturally focus on the searches at low mass where the discovery was made. In this region the five main decay modes studied are listed on Table 1. The first three channels are bosonic decays while the last two are fermionic decays. The Higgs boson mass resolution of the reconstructed final state is also shown on the Table. The excellent 1–2% resolution for fully reconstructed photon and lepton final states is a big factor on why these channels had the best sensitivity in the search. We present the highlights of the searches in these channels first. Only when germane we present distinctions between ATLAS and CMS.

3.1. Searches for $H \rightarrow \gamma\gamma$

The $H \rightarrow \gamma\gamma$ decay branching ratio is small as it can only proceed through loop diagrams. However the large inclusive production cross section and the distinct signature makes this a viable mode for a Higgs boson observation at low mass (< 160 GeV). At higher mass as can be seen in Fig. 2 there is basically no rate and therefore no sensitivity. The signal contains two isolated, high p_T (usually > 30 GeV), photons and possibly other objects from VBF and production mechanisms associated with vector bosons or top quarks. Both the ATLAS and CMS detectors were designed with excellent electromagnetic calorimeters that allow for precise measurements of photon (and electron) energies. This is paramount in the $H \rightarrow \gamma\gamma$ search as the continuum two-photon background, originating from multi-jet, multijet + photon and true di-photon production, is large relative to the number of signal events expected. Data is collected with di-photon triggers. Energy and isolation requirements are made on the photons to reduce backgrounds. Converted photons are also used and provide good energy and position resolution when electron pairs can be reconstructed by the trackers. The ATLAS experiment reduces background by using the longitudinal segmentation of the calorimeters to select photons that point to the hard interaction vertex. The CMS calorimeter is not segmented longitudinally and the experiment relied on information from the tracking system to resolve the most likely collision point from which the photons originated.

Several effects affect the precision with which the photon energy and direction are measured and the level of background relative to signal events. These include the various criteria used to identify photons, the photon p_T , photon conversions, isolation, the location of the photon in the detectors, and the presence of other objects, such as jets, in the event. To optimize the sensitivity of the search the experiments divide the two-photon event sample in multiple categories characterized by these properties. The search for the Higgs boson was performed as a fit to the di-photon invariant mass distribution using a smooth background functional form plus a narrow peak to describe the possible contribution for signal. This exercise is repeated at the different assumptions for Higgs boson mass. Each category is

Fig. 15. (a) Invariant mass of diphoton events in the ATLAS experiment. The results are presented with and without event weighting by expected signal to background ratio. (b) Invariant mass of diphoton events in the CMS experiment with events weighted by expected signal to background ratio and the unweighted distribution shown as an inset.

treated separately and the final result of the search is the combination of the results from all categories. The most challenging part of the analysis from the instrumental point of view was to maintain the precision of the calibration of the electromagnetic calorimeters in a high radiation environment. This required careful and continuous monitoring and recalibration. From the analysis side, in addition to the optimization by categories, the challenge was to describe the background shape in a robust manner. This was accomplished directly in data by testing several different choices of functional forms and by careful study of the systematic uncertainty associated with that process.

Initially the experiments were able to exclude the production of a Higgs boson at the rate predicted by the SM at several mass ranges in which there were no excess of events above the background expectation. However in the mass region around 125 GeV there was an excess of events in both CMS and ATLAS that became larger as the dataset sizes increased. The ATLAS di-photon invariant mass distributions, both weighted by signal to background ratio and unweighted are shown in Fig. 15(a). The corresponding CMS diphoton invariant mass distributions are shown in Fig. 15(b). The small signal-to-background ratio was compensated by the sharp resolution of the mass peak and a few hundred events consistent with the decay of a new particle can be clearly seen.

A statistical analysis to quantify these excesses was performed and in July 2012, the ATLAS experiment observed a 4.5σ excess of events compatible with a narrow resonance of mass 126.5 GeV with a signal strength of 1.9 ± 0.5 times the SM expectation. The CMS experiment observed a 4.1σ excess of events compatible with

a narrow resonance of mass 125 GeV with a signal strength of 1.6 ± 0.4 times the SM expectation. The strong evidence seen by both experiments in this single $H \rightarrow \gamma\gamma$ decay mode indicated that a new boson had been observed and, very importantly, strongly disfavored its spin value to be 1. The next piece of evidence for the existence of such a particle came from another low decay rate process, $H \rightarrow ZZ$, as described here below.

3.2. Searches for $H \rightarrow ZZ^{(*)} \rightarrow lll$

The $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ channel was used at the LHC to search for the Higgs boson in a broad mass range, roughly from one hundred and up to a few hundred GeV. The 4-lepton mode (where electrons and muons are considered) is one of the Higgs boson decays with smallest rate but it has the advantage that it can be fully reconstructed. The main background processes are: electroweak ZZ production, Z + jets, and $t\bar{t}$ production. At low mass the background yield is relatively small, after adequate requirements are made on the leptons p_T , and comparable to what is expected from a 125 GeV Higgs boson. The Higgs boson signal is a narrow resonance in the 4-lepton invariant mass distribution while background processes have a smooth continuous shape. To maximize the number of signal events, because of the four leptons in the final state, the challenges are to use the largest possible fiducial regions for lepton detection and to use advanced techniques in lepton identification, such as multivariate discriminants.

Data is collected using single and dilepton (CMS) triggers. The CMS experiment improves mass resolution by using an algorithm designed to detect and recover the momentum of final state photons radiated by the leptons. ATLAS incorporates a similar technique as part of its electron momentum fit. The main SM ZZ background is estimated from simulation normalized to NLO calculations. The backgrounds from Z + jets and $t\bar{t}$, where some of the leptons originated from b -quark decays or from fakes, are estimated from control regions in data. The performance of the four-lepton search including selection efficiency estimates and the scale and resolution of the four lepton invariant mass is tested by both experiments by searching for the four-lepton final state produced by single Z -boson production where one of the decay leptons radiates a photon that converts to a lepton and anti-lepton pair, $Z \rightarrow 4\ell$. Both experiments observed this process at a rate consistent with SM expectations and therefore validate nicely all analysis steps towards the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ search.

In addition to the reconstructed 4-lepton invariant mass the CMS experiment implemented a matrix element likelihood discriminant (MELA) that uses the angular information of the 4-lepton final state, as expected from the spin zero and even parity nature of the Higgs boson.

Large regions at high mass were initially excluded: the 131–162 GeV and 170–460 GeV ranges for ATLAS, and the 131–162 GeV and 172–525 GeV ranges for CMS. The regions that were not excluded were just above the on-shell WW

Fig. 16. (a) The 4-lepton invariant mass distribution from the ATLAS experiment. The data is displayed as point and the background expectation as a histogram. Several SM Higgs boson signal contributions are included for different hypothetical Higgs boson masses. Background Z + jets and $t\bar{t}$ bottom, background ZZ middle and Higgs boson signal top. (b) A two dimensional plot of matrix element likelihood versus four lepton invariant mass from the CMS experiment. Data is shown with event by event mass uncertainties while the expectation of a 125 GeV SM Higgs boson is superimposed as a temperature plot. The central region around 125 GeV is highest in probability.

production threshold, where the WW branching ratio dominates, and the low mass region where a small excess, of about a dozen events per experiment, was observed.

The ATLAS experiment estimated a significance of 3.4 sigma for this excess, compatible with a narrow resonance of mass 125 GeV with a signal strength of 1.3 times the SM expectation. Figure 16(a) shows the ATLAS 4-lepton invariant mass distribution.

The evidence presented by both experiments of a narrow resonance with decays to ZZ indicated the observation of a new boson. The angular information used by CMS weakly favored the spin zero and even parity quantum numbers for the new boson though no definitive measurement of these properties was possible with the data available at the time. Figure 17 shows a candidate event for $H \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$ from the CMS experiment.

3.3. Searches in $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$

The $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ channel has a large rate but the neutrinos in the final state preclude the full reconstruction of m_H . Still, some features of the signals can be exploited to result in relative good sensitivity for this search. The helicity analysis of a scalar Higgs boson decaying into two W -bosons implies that the two leptons tend to be collinear, with a small azimuthal separation. Kinematical distributions such

Fig. 17. A CMS candidate event for $H \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$. The two muons are identified in the outer muon chambers and the two electrons in the electromagnetic calorimeter.

as the invariant mass of the two leptons, $m_{\ell\ell}$, and the transverse mass of the leptons and $\cancel{E}_T$, m_T , also provide some separation power from background processes. The primary backgrounds are SM direct diboson production, W + jets, Drell–Yan, single top, and $t\bar{t}$. The reduction of the various backgrounds and the accurate estimate of their contribution are the major challenges in this channel.

Data is collected using triggers that require one or two leptons above a certain p_T threshold determined by the necessity to maintain the trigger rates at a reasonable level. The $\cancel{E}_T$ is required to be relatively large in order to reduced Drell–Yan and multijet backgrounds. The analysis is performed in categories that distinguish the different lepton flavor content and the number of accompanying jets in the event. Jets consistent with originating from b -quarks are vetoed to reduce contribution from top-quark processes. The jet content of the events helps separate productions processes, hence different level of signal to backgrounds subsamples can be selected for a more optimal sensitivity. For example, the two-jet category is used to optimize for VBF production by selecting jets with a large gap in pseudorapidity. In events with no additional jets the dominant background is non-resonant electroweak WW production. In events with same-flavor leptons the Drell–Yan background is largest, while $t\bar{t}$ and W + jets contribute to all categories. Other backgrounds are smaller in comparison. Control regions in data, depleted from signal, are used to ensure that the background composition is well-understood.

Fig. 18. Distribution of the transverse mass in the 0-jet and 1-jet WW analyses of ATLAS, with both $e\mu$ and μe channels combined. The expected signal for $m_H = 125$ GeV is shown stacked on top of the background prediction.

As a final discriminant, the ATLAS experiment used the m_T distribution, shown in Fig. 18, while CMS used a multivariate discriminant. With this channel the two experiments extended the sensitivity for a Higgs boson all the way down from the several hundred GeV and to the lower masses, near 125 GeV. ATLAS excluded the 137–261 GeV mass range and CMS the 129–520 GeV range. Both experiments observed a small excess of events at $\simeq 125$ GeV. The ATLAS excess had a local significance of 2.8σ corresponding to a signal strength of 1.4 ± 0.5 times the expected SM rate, assuming a Higgs boson mass of 125 GeV. The CMS experiment local significance was 1.6σ . Even though these excesses were not as compelling as those found in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ channels, the fact that they occurred in the mass region around 125 GeV added confidence in the combined result.

3.4. Searches in $H \rightarrow \tau^+\tau^-$ and in $H \rightarrow b\bar{b}$

The attempt to observe directly the fermionic decays of the Higgs boson into particles of the 3rd generation (i.e. in pairs of τ leptons or b quarks) was an essential part of the search at the LHC, as it would help complete the understanding of the properties of the new boson by measuring its Yukawa couplings to these fermions.

The event yields in the $H \rightarrow \tau^+\tau^-$ channel are quite large at low m_H , between 100–150 GeV. The high-efficiency identification of τ leptons that decay hadronically (64% of the time) is one challenge that the LHC detectors have been able to meet, resulting in good sensitivity for the searches in these modes. Another challenge is to reconstruct as well as possible the mass of a di-tau resonance. The application of multivariate analysis techniques, that take into account the $\cancel{E}_T$, has enabled to reconstruct such states with mass resolutions of $\sim 15\%$. The $Z \rightarrow \tau^+\tau^-$ provided an excellent calibration process in which to test the mass reconstruction methods and measure the tau identification efficiency. The experiments studied separately events

with zero, one, or two associated jets and oppositely charged τ lepton pairs in the following $\tau\tau$ decay final states: ee (ATLAS), $\mu\mu$, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$ (ATLAS), where e indicates $\tau \rightarrow e\nu\nu$, μ indicates $\tau \rightarrow \mu\nu\nu$, and τ_h indicates the τ lepton decaying to hadrons and a τ neutrino. In events with two jets the experiments targeted the VBF production process by requiring the jets to be in the forward regions of the detector and to have a rapidity gap between them. This is the mode with best sensitivity.

Data were collected on triggers that required one or two charged leptons and in the ATLAS experiment one trigger required two high p_T τ_h candidates ($\tau_h\tau_h$). The main backgrounds are Drell–Yan production and W + jets production where one jet is misidentified as a τ lepton. Multijet QCD processes and $t\bar{t}$ production are minor backgrounds. To enhance the presence of a possible signal relative to backgrounds, the leptons or sum of hadronic decay products are required to have substantial transverse energy and the $\cancel{E}_T$ from undetected neutrinos is required to be collinear with the direction of the dilepton system.

With the datasets analyzed at the time of the discovery the experiments reached good sensitivities but not enough to have detected the presence of a Higgs boson in these channels. The $\tau\tau$ invariant mass obtained in the CMS vector boson fusion analysis is shown in Fig. 19.

With about 5 fb^{-1} of 7 TeV data, and for Higgs boson masses in the 110–150 GeV range, the ATLAS experiment reached sensitivities to set limits on the $H \rightarrow \tau^+\tau^-$ production rate in the range of 3–11 times that of the expected production rate from the SM. The CMS experiment used in addition about 5 fb^{-1} of 8 TeV data to reach sensitivities in the 110–145 GeV mass range to set limits at a level 1.3–2.4 times the SM rate. At 125 GeV the actual limit set by CMS was 1.1 times the SM

Fig. 19. Distribution of the $\tau\tau$ invariant mass in the combined 7 and 8 TeV data sets for the VBF category of the CMS $\tau^+\tau^-$ analysis. The expected signal for $m_H = 125 \text{ GeV}$ is shown stacked on top of the background prediction.

expected rate. With the full statistics of the Run 1, accumulated by the end of 2013, first evidence for $H \rightarrow \tau\tau$ was then obtained by both collaborations.

The $H \rightarrow b\bar{b}$ decay occurs with the largest branching fraction, about 58% at a Higgs boson mass of 125 GeV. However, the QCD $b\bar{b}$ production yields at the LHC are seven orders of magnitude larger than those from direct Higgs boson production. Therefore in their search for $H \rightarrow b\bar{b}$ the LHC experiments resorted mainly to the associated production mode, VH. Three channels, with leptons and $\cancel{E}_T$ in the final state, were considered: $WH \rightarrow \ell\nu b\bar{b}$, $ZH \rightarrow \ell^+\ell^- b\bar{b}$, and $ZH \rightarrow \cancel{E}_T b\bar{b}$ where the Z decays to neutrinos, “observed” as $\cancel{E}_T$. Even though these final states are rather distinct, several background processes with similar final states, but with significantly larger yields, present a formidable challenge. These processes include $V + \text{jets}$, $t\bar{t}$, single top, dibosons, and QCD multijet production with misidentified leptons.

Data were collected through several trigger paths, including single or double leptons, $\cancel{E}_T$, and requiring jets when needed. Two “ b -jets”, which are jets tagged by an algorithm as originating from b quarks, were required in all channels, reducing backgrounds very significantly. Another requirement made for all channels that helped reduce backgrounds further was to impose a significant p_T “boost” in the reconstructed $H \rightarrow b\bar{b}$ and vector bosons. In order to maximize the sensitivity, the analyses were performed separately in different boost regions. In channels with $\cancel{E}_T$ the multijet background is reduced to acceptable levels by requiring that the $\cancel{E}_T$ is not near any of the jets in the event. The most differentiating variable between signal and background is the invariant mass, $m_{b\bar{b}}$, of the two b -jet system. For $H \rightarrow b\bar{b}$ a peak in $m_{b\bar{b}}$ consistent with the jet energy resolution is expected, whereas for all backgrounds the resulting distribution is smooth without any structure. The ATLAS experiment used this distribution as the final discriminant in which to search for the $H \rightarrow b\bar{b}$ signal. The CMS experiment used a regression technique that improves on the energy resolution for generic jets in order to sharpen the mass peak, and used a multivariate discriminant, that included $m_{b\bar{b}}$ together with several other kinematical variables, as a final discriminant in the search. The ATLAS (CMS) experiment searched for a Higgs boson in the range 110–130 GeV (100–135 GeV) using 4.7–5.0 fb⁻¹ of 7 TeV collision data per experiment, while the CMS experiment additionally included 5.1 fb⁻¹ of 8 TeV collision data. The CMS analyses had sensitivity to set limits on order one to five times the expected SM Higgs boson cross section, depending on the mass, achieving a sensitivity of 1.6 σ at a Higgs boson mass of 125 GeV. In this channel, observation will have to wait for more data, and should be achieved in the Run 2 of the LHC.

4. The Discovery of the Higgs Boson

At the end of 2011, based on ~ 5 fb⁻¹ of 7 TeV data, ATLAS and CMS presented results at the CERN council with some small signal at the 2.5 σ level around 125 GeV, so 2012 data became eagerly expected. At the Moriond Conferences in

March 2012, the LHC experiments did not update their Higgs boson results but the Tevatron experiments presented a combination based on $\sim 10 \text{ fb}^{-1}$ of data which also showed a $\sim 2.5\sigma$ excess, but in a region of mass much wider (120–140 GeV), which was understandable since the signal was expected to be dominated by $H \rightarrow b\bar{b}$ decays which forms experimentally a wide resonance.

But the real breakthrough came on the 4th of July 2012. In a special seminar at CERN, the independent discovery of the Higgs boson was announced by the ATLAS and CMS experiments as detailed here below. To better characterize this discovery, we first present the last steps of the analyses.

Before the discovery, all Tevatron and LHC experiments were computing limits on the production cross section for a standard theory Higgs as a function of its mass, combining different searched processes. To facilitate comparisons with the SM and to accommodate analyses with different degrees of sensitivity and acceptance for more than one signal production mechanism, the limits were divided by the SM Higgs boson production cross section, as a function of Higgs boson mass, for test masses for which the experiments performed dedicated searches in different channels. A value of the combined limit ratio which is less than or equal to one indicates that particular Higgs boson mass is excluded at the 95% C.L. At the LHC the limits are calculated using the modified frequentist CL_s approach. At the Tevatron, both CL_s and a Bayesian technique were used. The limits were generally determined using the MVA output distributions or the invariant mass distributions, together with their associated uncertainties, as discriminating inputs to the limit setting procedure.

Systematic uncertainties were accounted for by nuisance parameters which were assigned an *a priori* probability distribution. Correlations between the uncertainties were taken into account. To diminish the impact of the nuisance parameters the profile likelihood distribution were maximized over the nuisance parameters. Each background was allowed to vary within its uncertainties by varying the nuisance parameters in the fitting procedure, while the fit was constrained to lie within the uncertainties.

This framework can also produce statistical results quantifying the properties and the expectation for a signal. Given the SM expectation for signal contributions, the expected p -value or probability for backgrounds to fluctuate to the statistical significance of the expected signal can be computed. Similarly, given an excess in the data, the observed p -value can be computed and evidence or discovery will be obtained if the p -value reaches the equivalent probability of 3 or 5 standard deviations.

4.1. ATLAS and CMS discoveries

For the discovery, each analysis channel was analyzed separately and within each experiment the Higgs boson search results were then combined.^{32,33}

Fig. 20. (a) The ATLAS experiments combined upper limit as a function of the Higgs boson mass between 100 and 600 GeV. Solid black: observed limit/ σ_{SM} ; Dashed black: median expected limit/ σ_{SM} in the background only hypothesis. Colored bands: $\pm 1, 2\sigma$ distributions around median expected limit. The excess around $m_H = 125$ GeV is clearly visible. (b) The CMS experiments combined upper limit as a function of the Higgs boson mass between 100 and 600 GeV. Solid black: observed limit/ σ_{SM} ; Dashed black: CMS expected limit/ σ_{SM} in the background only hypothesis. Colored bands: $\pm 1, 2\sigma$ distributions around median expected limit. The excess around $m_H = 125$ GeV is clearly visible.

Over a large region of masses the LHC experiments observed no evidence for a Higgs boson. The LHC data showed a consistent picture with the exclusion, typically by multiple channels, of a high mass SM Higgs boson. At high mass the ATLAS experiment excluded the production of a SM Higgs boson with masses from 131 to 559 GeV at 95% C.L. and the CMS experiment excluded a region from 128 to 600 GeV at 95% C.L., where 600 GeV was the limit of the search range. At low mass the ATLAS experiment excluded the production of a SM Higgs boson with masses from 111 to 122 GeV at 95% C.L., while the CMS experiment excluded the region from 110 to 122.5 GeV. The combined ATLAS and CMS limits are presented in Figs. 20(a) and 20(b) respectively.

At low masses the experiments had the sensitivity to exclude or observe the Higgs boson. The sensitivities for observation of a signal were quantified as an expected p -value for the background to fluctuate to a signal as large as the median expectation for a SM Higgs boson. The combined expected p -value at $m_H = 125$ GeV was 4.9σ for the ATLAS experiment and 5.8σ for the CMS experiment. In the region around 125 GeV both experiments observed an excess of events in the bosonic final state search channels. The experiments evaluated the p -values for each channel separately and for the entire combination and compared those values with the expected background only p -values given a SM Higgs boson as a function of mass (see Figs. 21(a), 21(b)). Information quantifying the most significant excesses in the individual search channels is summarized along with the most significant combined excess from each

Fig. 21. (a) ATLAS local significance³² for each search channel and the combination. The observed significance are shown with solid curves, and the median expected significance assuming a signal is present at the SM strength are shown with dashed curves. A dotted line indicates the 6σ threshold. The highest local significances of the ZZ and $\gamma\gamma$ channels are 3.4σ and 4.5σ respectively while the combined significance of all channels 5.9σ . (b) CMS local p -values.³³ The observed p -values are shown with solid curves, and the median expected p -value for the combined search assuming a signal is present at the SM strength is shown with a dashed curve. Horizontal lines indicate the $1\sigma - 7\sigma$ thresholds. The highest local significances of the ZZ and $\gamma\gamma$ channels are 3.1σ and 4.1σ respectively while the combined significance of all channels 5.1σ .

Table 2. The most significant excesses seen in ATLAS and CMS results in the different channels and at the masses where they were seen, and their combined significances.

Topology	ATLAS Significance and Mass	CMS Significance and Mass
$H \rightarrow WW \rightarrow \ell\nu\ell\nu$	2.8σ 125.0 GeV	1.6σ 125.0 GeV
$H \rightarrow ZZ \rightarrow 4\ell$	3.4σ 125.0 GeV	3.1σ 125.6 GeV
$H \rightarrow \gamma\gamma$	4.5σ 126.5 GeV	4.1σ 125.0 GeV
Combined Significance	5.9σ 126.0 GeV	5.0σ 125.3 GeV

experiment in Table 2. Both experiments observed a Higgs boson signal with local significances above the evidence level of 3σ in the ZZ and $\gamma\gamma$ decay modes and combined significances of 5.9σ at $m_H = 126$ GeV for the ATLAS experiment and 5.0σ at $m_H = 125.3$ for the CMS experiment. These two observations characterized in an unambiguous way the discovery of a new particle with mass of approximately 125 GeV. The decay modes in which the particle was seen also indicated that the particle is a boson and plays a role in the mechanism of electroweak symmetry breaking.

(a)

(b)

Fig. 22. (a) ATLAS best-fit signal strength for all SM Higgs boson decays, for $m_H = 125 \text{ GeV}/c^2$. (b) CMS best-fit signal strength for all SM Higgs boson decays, for $m_H = 125 \text{ GeV}/c^2$. The shaded band corresponds to the $\pm 1\sigma$ uncertainty on the full combination.

The CMS and ATLAS collaborations measured right away several properties to understand the compatibility of the observed boson with the SM Higgs boson and presented the results in their papers reporting the observations.^{32,33} The experiments measured the cross section for Higgs boson production in each decay channel and also globally combining all decay channels. The results were presented as a ratio to the expected SM values in Figs. 22(a) and 22(b) for the ATLAS and CMS experiment respectively. The combined signal strengths measured by the experiments were 1.4 ± 0.3 for ATLAS and 0.87 ± 0.23 for CMS compatible with the SM Higgs boson expectation. Individual signal strengths in the most sensitive modes were discussed in the sections on individual searches.

The fully reconstructed decays of the Higgs boson $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ have excellent mass resolution. The $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ decay mode has substantial rate but poor mass resolution due to the two neutrinos in the final state. The ATLAS experiment measured a mass for the observed boson of $m_H = 126.0 \pm 0.4(\text{stat}) \pm 0.4(\text{sys}) \text{ GeV}$ using all three decay modes. The individual fits in a two dimensional analysis of signal strength versus mass are shown in Fig. 23(a). The CMS experiment used the fully reconstructed $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ modes to measure a mass of $m = 125.3 \pm 0.4(\text{stat}) \pm 0.5(\text{sys}) \text{ GeV}$. The individual and combined fits are shown in Fig. 23(b). The results were compatible with limits from previous searches, and the prediction of the SM Higgs boson mass from constraints derived from electroweak measurements.

If the observed boson is involved in the mechanism of electroweak symmetry breaking, the measurement of its coupling to the W and Z bosons is a crucial

Fig. 23. (a) The ATLAS two dimensional fit for the cross section compared to the SM expectation and the Higgs boson mass for highest significance decay channels. (b) The CMS two dimensional fit for the cross section compared to the SM expectation and the Higgs boson mass for highest significance decay channels and the combined fit using those channels.

discriminant. The production and decay rates measured by the experiments were compatible with the SM. The ratio of the W and Z couplings can be computed by dividing the production times decay rates for $H \rightarrow WW$ and $H \rightarrow ZZ$ since the production of the Higgs boson takes place via the same mechanisms. The ATLAS experiment measured $R_{WZ} = 1.07^{+0.35}_{-0.27}$ and the CMS experiment measured $R_{WZ} = 0.9^{+1.1}_{-0.6}$ consistent with the SM expectation where both experiments normalized the measurement so that the expected value in the SM is one.

In summary, the LHC experiments extended the LEP exclusion to 122.5 GeV and further excluded a SM Higgs boson with mass between 128 and 600 GeV. The ATLAS and CMS experiments both observed a significant excess of events in the region around 125 GeV with evidence for the production of a new boson in the ZZ and $\gamma\gamma$ decay modes, with observed local significances of 4.5σ and 4.1σ in the $\gamma\gamma$ mode, 3.4σ and 3.1σ in the ZZ mode. Significant signals (2.8σ and 1.6σ) were also observed in the $H \rightarrow WW$ decay mode, while the observed significance in the fermionic modes ($H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$) was weak, which was not unexpected given the low expected significance in these modes with that luminosity. When combining all their channels, both experiments independently reported the discovery of a new boson and provided first measurements of its fundamental properties, in agreement with those expected from a SM Higgs boson with a mass close to 125 GeV.

Fig. 24. (a) Observed and expected 95% C.L. upper limits on the ratios to the SM cross section, as functions of the Higgs boson mass for the combined CDF and D0 analyses. The bands indicate the 68% and 95% probability regions where the limits can fluctuate, in the absence of signal. (b) The background p -values $1-CL_b$ as a function of the Higgs boson mass (in steps of 5 GeV), for the combination of the CDF and D0 analyses. The two bands correspond respectively to the regions enclosing 1σ and 2σ fluctuations around the median prediction in the signal-plus-background hypothesis at each value of m_H .

4.2. Tevatron combined results

When at the end of June 2012 CERN announced a special seminar for July 4th, the Tevatron released its latest CDF + D0 combination. These results were also pointing to an excess in the low mass region, but with much less significance as shown in Fig. 24(a) which shows the ratios of the 95% C.L. expected and observed limits to the SM cross section, and in Fig. 24(b) which shows the p -value $1-CL_b$ as a function of m_H . The smallest observed p -value corresponded to a Higgs boson mass of 120 GeV and had a local significance of 3.0σ . The width of the dip from 115 to 135 GeV was consistent with the combined resolution of the $H \rightarrow b\bar{b}$ and $H \rightarrow W^+W^-$ channels. The effective resolution of this search came from two independent sources: the reconstructed candidate masses, which directly constrain m_H , and the expected cross sections times the relevant branching ratios for the $H \rightarrow b\bar{b}$ and $H \rightarrow W^+W^-$ channels, which are functions of m_H in the SM. The observed excess in the $H \rightarrow b\bar{b}$ channels coupled with the outcome in the $H \rightarrow W^+W^-$ channels determined the shape of the observed p -value as a function of m_H . The strongest sensitivity at low mass comes from the $H \rightarrow b\bar{b}$ channels. The largest local significance in the combination of $H \rightarrow b\bar{b}$ channels was 3.3σ at a mass of 135 GeV, while it was 2.8σ at 125 GeV.²¹

The signal strength was allowed to vary as a function of m_H in the fit of the signal-plus-background hypothesis to the observed data over the full mass range.

Fig. 25. (a) The best fit signal cross section of all CDF and D0 search channels combined shown as a ratio to the SM cross section as a function of the tested Higgs boson mass. The horizontal line at 1 represents the signal strength expected for a SM Higgs boson hypothesis. The grey band shows the 1σ uncertainty on the signal fit. (b) Best-fit signal strength for the three most sensitive boson decay modes at the Tevatron, for $m_H = 125 \text{ GeV}/c^2$. The shaded band corresponds to the $\pm 1\sigma$ uncertainty on the full combination.

The resulting best-fit signal strength is shown in Fig. 25(a), normalized to the SM prediction and is within 1σ of the SM expectation for a Higgs boson signal in the range $115 < m_H < 140 \text{ GeV}$. The largest signal fit in this range, normalized to the SM prediction, was obtained between 120 and 130 GeV. The excess in signal-strength around 200 GeV occurred in a region of low expected sensitivity ($\sim 1\sigma$) and with an unphysically narrow mass range, it thus could not be attributed to a SM Higgs boson signal at high mass.

The global significance of approximately 3.1σ obtained by this combination, provided evidence for the production of a resonance in the $b\bar{b}$ dijet mass distribution, produced in association with a massive vector boson, compatible with the Higgs boson discovered at CERN, given the mass resolution in this final state. This also provided the first evidence for fermionic decays of this boson. This was particularly interesting since the signals in the fermionic channels were then insignificant at the LHC, hence the Tevatron result supported the interpretation of a SM-like Higgs boson for this newly discovered particle.

The measured cross section times branching ratio $\sigma_{WH} + \sigma_{ZH} \times \mathcal{B}(H \rightarrow b\bar{b})$ had a value of $0.23^{+0.09}_{-0.08} \text{ pb}$ for $m_H = 125 \text{ GeV}$, consistent with the corresponding SM prediction of $0.12 \pm 0.01 \text{ pb}$. The best fit signal cross section from the combined CDF and D0 analyses separated into the different Higgs boson decay channels is shown in Fig. 25(b), assuming $m_H = 125 \text{ GeV}$. The three decay channels shown are all in agreement with the standard theory prediction.

In summary, at the time of the Higgs discovery by the LHC experiments, the Tevatron had an excess of data events with respect to the background estimation in the mass range $115 < m_H < 135$ GeV. The p -value for a background fluctuation to produce such an excess corresponded to a significance of 3σ at 125 GeV. The largest excess was observed in the $H \rightarrow b\bar{b}$ channels, with a global significance of $\approx 3.1\sigma$. The CDF and D0 collaborations could thus report evidence “right away” for the production of a resonance in the b flavored dijet mass distribution produced in association with a massive vector boson, consistent with the new boson observed by the LHC collaborations. The measured cross section for this process was consistent with the cross section expected for a SM Higgs boson of 125 GeV produced in association with a W or a Z boson. Unfortunately, since the data taking was already stopped when the LHC discovery was made, this evidence could not be strengthened further. It showed however that the boson newly discovered through its bosonic decay modes was behaving as expected in the fermionic decays, in spite of the limited statistics. Final results consistent with the results presented above, with a slightly lower measured production cross section, were published in 2013.⁶¹

5. Conclusion and Prospects

The search for the Higgs boson lasted for more than 30 years and was performed at the three last major colliders. In July 2012, the LHC experiments finally discovered a new boson with mass around 125 GeV, with evidence for this particle in several bosonic decay modes. The production and decay modes that were observed indicated right away that this boson plays a role in the mechanism of electroweak symmetry breaking and also in the mass generation for the quarks. The Tevatron experiments reported evidence for a particle, produced in association with W or Z bosons and which decays to $b\bar{b}$, with a mass compatible to that reported by the LHC experiments. The properties of this boson were compatible with those expected for a SM Higgs boson but more study were required to fully explore the nature of this discovery. This research program continued until the end of Run 1 (2014) and allowed to accumulate more precise results as those presented here, as is discussed in the other experimental contribution on Higgs properties in this Book. Furthermore it will continue for many more years at the upgraded LHC and later, with upgraded detectors. While the discovery of a new boson with properties indicating that it plays a role in electroweak symmetry breaking is a major breakthrough in fundamental physics, we all hope that physics beyond the standard model will be revealed by the precise study of this particle and its associated potential.

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