Seminar – 1st year of the Physics 2nd cycle

The hunt for the Higgs boson

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Abstract

For many years the “periodic table” of the Standard Model has been incomplete, because of the elusive Higgs boson particle. In this seminar I will in short discuss the theory of the Higgs boson, search strategies and where do we currently stand experimentally on the subject with findings from the LHC, LEP and Tevatron.

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1 Introduction

Higgs boson, the holy grail of particle physics...It has come a long way from just a hypothesis, a mathematical trick to make the theory more feasible. There are now indications, that it is no joke.

We live perhaps in a unique time, where the discovery of “Higgs” might become a reality. Journalists went so far as to dub it ‘the God particle’. While such nicknames are nothing but exaggerations, the discovery of the Higgs boson, will mean that for the last 50 years we’ve been mostly on the right track, it will be the so called ‘experimentum crucis’, that will round up and complete the Standard model experimentally as well.

The theory of particle physics has advanced to such an extent, that many are wondering if this still makes any sense at all and the problem is, that some theories have begun to border on metaphysics, rather than physics\(^1\). New theories and models have been proposed and we don’t know which to follow.

Despite what many theorists would like to think, physics is an empirical science, we study nature. And so theory of nature must be in agreement with nature itself. If it doesn’t describe it, it’s not physics anymore.

So in truth it doesn’t really matter if we confirm the Higgs boson or reject it (although it would be really appreciated if we did), because either way it will give us hints and clues on how to continue our description of nature.

2 Standard Model Higgs boson

Contrary to common belief, Higgs bosons are already part of the Standard Model (SM). In the sixties, new questions arose in the world of particle physics: the theories weren’t renormalizable\(^2\), and the question of the hierarchy. While such a mechanism cannot give the direct answer to the latter\(^3\), it does provide the masses for the gauge bosons and fermions.

The hypothesis is that our observable space is immersed in a field, which spontaneously breaks the symmetry of the Lagrangian density \(\mathcal{L}\). The original Lagrangian retains the symmetry (all gauge bosons and particles are massless), but the field is the one makes particles behave, as though they had mass.

2.1 The Higgs field

Let us make a quick overview of some very basic theory behind the Higgs boson just so we will get familiar with some of the physical observables.

We could start all with Quantum Field Theory (QFT). However, since the majority of students is unfamiliar with it, we’ll commence with a different and a more qualitative approach.

\(^1\)String theory is such an example.

\(^2\)Renormalizable theories have singularities which can be removed using redefinition (renormalization) of non-physical parameters. Lagrangian is in that case a part of the renormalization group – giving us the freedom to gauge it accordingly.

\(^3\)Though it is responsible for the electroweak symmetry breaking.
The Higgs mechanism is intimately connected with the electroweak theory. With the discovery of the weak interaction, physicists were puzzled as to how to parametrize it. Fermi suggested to do the same thing as before for the electromagnetic, just change the constant. Later they fixed it with additional ‘γ₅’ terms to include left-handedness. However there was still something wrong with the theory. It wasn’t renormalizable. While such theories can occur at anytime, and are allowed in physics, they are more complex and so they tried to “fix” electroweak theory.

Of course, when Fermi first wrote down his low-energy parametrization it was just a “contact” interaction. In order to fix it, theorists tried substituting the coupling with a propagator, containing mass of the weak bosons. Even so, with introducing masses of the weak bosons “by hand” into the Lagrangian, they didn’t manage to make the theory renormalizable.

Then in the early sixties, a group of physicists independently realized that the theory can be made renormalizable by using the electroweak symmetry, which would then be spontaneously broken through another, complex scalar field. This mechanism was later dubbed the Higgs mechanism, after one of the theorists who postulated it.

Just like we can remember from the classical Hamiltonian and Lagrangian mechanics, we can substitute the coordinates with fields [1]: one way to introduce the field, φ, is with a new potential in the Lagrangian

$$V(\phi) = \mu^2 |\phi|^2 + \frac{\lambda}{4} |\phi|^4,$$

like it’s shown in the fig. 1.

![The Higgs potential](image)

Figure 1 – The Higgs potential for the complex field φ. Parameter λ is always greater than zero.

Alternatively $$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$$, like in [2, pg. 18], which only changes this: $$\langle \phi \rangle \sqrt{2} \rightarrow \langle \phi \rangle / \sqrt{2}$$ and vice-versa. I used this fixing in equations (4), (5) and (6), which in turn look slightly different from what the book suggests. This parametrization also changes the definition of the Higgs boson mass, $\mathcal{M}_H$, like in [3, pg. 267]. In the one I used, the constants are set in such a way, that the $\mathcal{M}_H = \sqrt{-\mu^2}$.
Lagrangian retains the symmetries of the potential. But to solve the problems via QFT, we need to make a series expansion around the minimum. However, for negative $\mu^2$ we have two of them. And as soon as we start to make expansion around either of those, we break the symmetry. The new approximation from the expansion

$$\varphi \equiv \phi - \phi_+,$$

is then called the Higgs field [4], which, upon 2nd quantization, yields the Higgs bosons $- H$. We usually name the $\phi_+ \equiv \langle \phi \rangle$.

2.2 Properties of the Higgs field

The Higgs field boson is a scalar – it’s spin is theoretically zero, and it obeys the Klein-Gordon differential equation. It doesn’t carry any charge, colour or weak hypercharge.

We are dealing with mass here and so our field doesn’t have the usual translational symmetry (the ground state isn’t arbitrary)

$$\varphi \xrightarrow{\langle \phi \rangle} \varphi + C.$$

We can see this, because vacuum states are the ones, that give weak gauge bosons mass$^6$. Positive minimum of the potential (1) is referred to as the ‘vacuum expectation value’ [2], $\langle \phi \rangle$, which is obviously a nonzero quantity

$$\langle \phi \rangle \equiv \phi_+ = \sqrt{-\frac{2\mu^2}{\lambda}},$$

from which we can obtain the vacuum energy of the potential (which is quite irrelevant, but anyway),

$$V(\langle \phi \rangle) = V_0 = -\frac{\mu^4}{\lambda}. \quad (3)$$

The value of $\langle \phi \rangle$ is all that we need in order to give masses to the gauge bosons and fermions. For instance, masses of the $W^\pm$ and $Z$ bosons can be written as (see [2, pg. 19])

$$M_W = g_W \langle \phi \rangle \sqrt{2}, \quad M_Z = \frac{M_W}{\cos \theta_W} = \frac{g_W \langle \phi \rangle \sqrt{2}}{\cos \theta_W}. \quad (4)$$

Higgs bosons couple to themselves$^7$, to other bosons and to fermions. We have different possible couplings for each case. Fermions get their masses from the so called ‘Yukawa interactions’, and Higgs bosons couple to them through Yukawa couplings, $'g_f'$. For each fermion there might be different couplings, as the coupling strength is proportional to the fermion mass. Mass for a fermion $'f'$ can then be written as (see [2, pg. 19])

$$m_f = 2g_f \langle \phi \rangle = M_W \frac{g_f}{g_W} \sqrt{2}. \quad (5)$$

$^5$We can imagine, that such solutions aren’t symmetric around the $\phi = 0$ axis, though the original Lagrangian suggests that they are.

$^6$And because $L$ isn’t invariant on such transformations – we cannot move both minimums and retain the symmetry over the $\phi = 0$ axis.

$^7$They give masses to each other – self-coupling.
The vacuum expectation value has been theoretically set to \( \langle \phi \rangle = v / \sqrt{2} \), with \( v \approx 246 \) GeV [5, pg. 1], [2, pg. 21] for the theory to be renormalizable and experimentally confirmed to be \( \langle \phi \rangle \sim 174 \) GeV [2, pg. 19] (\( v \) is also a vacuum expectation state [5, pg. 1], but from the alternative definition of the Higgs potential \( V(\phi) \) [3, pg. 267]; people at CERN mostly use \( v \) instead of \( \langle \phi \rangle \)).

Parameter \( \sqrt{-\mu^2} \) from such \( V(\phi) \), defined in eq. (1) can be identified as the Higgs mass, which we can parametrize with this expression (see [2, pg. 21])

\[
M_H \equiv \sqrt{-\mu^2} = \sqrt{-\frac{2\mu^2}{\lambda}} \cdot \sqrt{\frac{\lambda}{2} \langle \phi \rangle} = \langle \phi \rangle \sqrt{\lambda/2} = v \sqrt{\lambda} = 246 \ \text{GeV} \cdot \sqrt{\lambda},
\]

so we see that \( \lambda \) is the remaining free parameter in the theory to compute the Higgs boson mass.

### 3 Search strategies at the LHC

Even if we don’t know all the numbers, we can still bound the mass of the Higgs boson, so that the theory will still have sense (tab. 1). Upper bound is based upon the scale where the SM breaks down\(^9\), lower bound is based on the \( \langle \phi \rangle \) stability and unitary constraints from the electroweak interaction.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Mass Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable ( \langle \phi \rangle )</td>
<td>( 130 \ \text{GeV} \lesssim M_H \lesssim 180 \ \text{GeV} )</td>
</tr>
<tr>
<td>Metastable ( \langle \phi \rangle )</td>
<td>( 115 \ \text{GeV} \lesssim M_H \lesssim 180 \ \text{GeV} )</td>
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</tbody>
</table>

Needless to say, the only way, physicists are considering to produce \( H \) is using high energy beam collisions in colliders. Hadron colliders are preferred, since they are the exploratory machines\(^{10}\). During the course of time there were three that were at least partially dedicated to the \( H \) hunt and got some results: electron–positron (LEP), proton–anti-proton (Tevatron) and proton–proton (LHC).

Why do we need such a high energy? When we are colliding protons, the problem is this that each proton behaves as a group of free particles (QCD effect). The constituents are then responsible for interactions. Each of them carries only a part of the total momentum. And it turns out that each valence quark carries approximately 1/6 of it. So in order to probe mass regions up to 1 TeV, we would need at least \( \sim 6 \) TeV energy. They decided to make it 7 TeV, just to be on the safe side.

The reason why this project was accepted and others were refused\(^{11}\), was probably because LHC is using the old LEP tunnel. But in order to make more energetic coll-

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\(^8\) There are still other free parameters, namely the coupling constants.

\(^9\) Perturbation theory fails to give us credible results.

\(^{10}\) While lepton colliders are precision machines.

\(^{11}\) Namely the UNK in the USSR and SSC in the USA.
sions, much stronger magnets were needed. In circular colliders, energy yield \(- E \text{ [TeV]}, \) accelerator circumference\(^{12}\) \(\rho \text{ [km]}\) and magnetic field strength \(B \text{ [T]}\), can be estimated using this formula

\[
B\rho \sim E \cdot \frac{3.36 \text{ T} \cdot \text{km}}{\text{TeV}},
\]

from which we obtain incredible \(B \sim 8.71 \text{ T}\) (using 7 TeV and 27 km). The temperatures needed to cool such strong magnets and keep them in the superconducting phase\(^{13}\) are so low, that the liquid helium coolant must be in the superfluid phase. This resulted in greater complications, since superfluid helium passes through most of the known materials as if through a strainer. Magnets are now expected to operate at \(B = 8.36 \text{ T}\).

In order to predict cross sections and branching ratios, theoretical models were used. The biggest problem was this: of all the possible reactions, that can take place, the cross section for the Higgs boson is lower by several orders of magnitude (fig. 2). For this reason, sufficiently high energy and detector luminosity have to be reached.

\[\text{Figure 2} - \text{Some cross sections at modern hadron colliders [6]. We can see that Higgs boson production is very rare. We are producing a lot of background (known events) and very little signal.}\]

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\(^{12}\)If there was just the radius then there would be a different equation.

\(^{13}\)We want this, so the current passes with no resistance and so we keep the energy losses low.
Higgs boson cross sections are low due to the fact that its couplings are proportional to mass. Ordinary matter is very light (electrons, up and down quarks) and so production rates are lower. Higgs couplings are by several orders of magnitude higher if we used boson collisions\textsuperscript{14}. 

So now that we have Higgs boson production within our reach (if it exists), let us consider the possible production channels (see fig 3).

![Theoretical Higgs boson production cross sections for the proton-proton collisions at the energy of collisions $\sqrt{s} = 14$ TeV. Computed by the TeV4LHC Higgs working group [7].](image)

**Figure 3** – Theoretical Higgs boson production cross sections for the proton-proton collisions at the energy of collisions $\sqrt{s} = 14$ TeV. Computed by the TeV4LHC Higgs working group [7].

### 3.1 Gluon fusion

The coupling constants for ordinary matter are actually so low, that at the LHC, Higgs boson will most likely be produced via the gluon fusion (fig. 4) – gluons form an intermediate top quark loop, to which Higgs boson can couple really well because of their 175 GeV mass. Higgs boson production is then more likely to occur at the loop order, rather than the tree order, which is rather surprising. This channel, however, has a lot of background and cannot easily be distinguished.

Even so, with our well defined BRs this is not enough. We need two signals in order to know that we produced the Higgs boson: we need some sort of “tagging” to determine the production mode as well. And so production modes with low background and some simple tagging mechanism are preferred. That’s why the gluon fusion, though it is the dominant production mode, isn’t preferred, since it isn’t distinctive enough (large backgrounds). This doesn’t mean that the channel is useless, it just means that Higgs boson identification through this channel is harder than the rest.

\textsuperscript{14}As we saw in one of the previous seminars, photon colliders look very appealing for this very fact.
3.2 Weak gauge boson fusion

Thankfully enough, the 2nd dominant mode, the weak gauge boson fusion (fig. 4), is quite distinctive: $W$ and $Z$ fusion processes. Such reactions can then be tagged quite easily and they also have low background [2, pg. 157]. Other possible way are annihilation processes – quarks annihilate through electroweak interaction. These are the so called ‘Drell-Yan’ processes, where off-shell $Z$ or $W$ radiates a Higgs boson [2, pg. 158]. These processes are preferred since through them we can directly measure the Higgs boson coupling to the weak gauge bosons.

We can then use the different decay modes in order to clearly distinguish between different channels and get a really clean signal.

3.3 Other modes

There are still other production modes, Higgs boson pair production, top quark fusion and the so called “associated production”, because in these reactions the Higgs boson is produced in association with other particles. These modes don’t play a crucial role in the Higgs discovery, since they are of a very low probability, but they will play more important roles later if the Higgs is discovered, since using the associated products we can measure the spin, charge conservation and other properties of the Higgs boson.

![Figure 4](image)

*Figure 4 – The most common production modes on the Feynman diagrams for better visualization.*

3.4 Higgs decay modes

Higgs boson decay width in that mass region is $10^{-21} \lesssim \Gamma \lesssim 10^{-23}$ s, so the we can only identify it indirectly from reconstruction, the transverse energy $E_T$, the transverse linear momentum $\vec{p}_T$ and through its decay products which are shown in the lower graph (see fig. 5).

Since Higgs couplings are proportional to masses of the particles, our surest bets are heavy particles. Cleanest channels are produced via weak gauge boson decays, which
subsequently decay into leptons, or into $q\bar{q}$ pairs, which produce the so called ‘jets’ of particles\textsuperscript{15}.

Of course the Higgs hunt takes place in all the channels, but the cleanest are, as said before, in the $H \rightarrow WW^{(*)}$ or $H \rightarrow ZZ^{(*)}$ decays. We must identify Higgs boson through subsequent decays.

The cleanest channel is $ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$, since we cannot get this situation in many ways. It is very unlikely to happen, but if it happens, it’s very likely to have come from the Higgs boson.

Then there are three others we really like to consider: $WW^{(*)} \rightarrow \ell^+\nu\ell^-\bar{\nu}$ and $WW^{(*)} \rightarrow \ell\nu q\bar{q}$ (two-jet event with missing $E_T$) and $WW^{(*)} \rightarrow q\bar{q}q\bar{q}$ (four-jet event).

\textbf{Figure 5} – SM Higgs boson branching ratios (ratio between this channel decay rate to total decay rate) including uncertainties. Plotted by LHC Higgs Cross Section Working Group \cite{8}.

4 Overview of past attempts

The attempt to finally complete the SM “periodic table” is by no means a new endeavour. Before LHC there have been several attempts to find the Higgs boson, and the ones who actually managed to obtain some results\textsuperscript{16} were at the LEP collider (CERN) and Tevatron (Fermilab).

Higgs bosons were sought both directly (did we get the Higgs boson?) and indirectly (if the Higgs boson exists, then certain parameters should have prescribed values). The main reason why they didn’t manage to get the Higgs boson was mostly due to the low energy reach of the colliders and consequently very low cross sections for production. Some detectors reported slight excess, while others managed to experimentally bound $M_H$.

\textsuperscript{15}Since we cannot have bare quarks they immediately “dress” themselves with additional quarks which then do the same until energy equilibrium has been reached. The remaining quarks are all bound hadron states. In this event we say that we get the jet of particles.

\textsuperscript{16}There are other results as well, but they didn’t have the same energy reach and they only served to exclude very low-mass Higgs boson, because they didn’t see anything.
Still, there were enough indications, which later served as a motivation for construction of the LHC [2].

4.1 LEP

Although the hunt for the Higgs particle has been popularized recently with the completion of the LHC, CERN made an attempt to find it before with their previous collider, LEP\textsuperscript{17}.

LEP was an $e^-e^+$ collider, which meant cleaner signals and no QCD background, which modern hadron colliders now have to face. The dominant production process was associated production via $e^+e^- \rightarrow HZ$ [5]. It was also possible to produce Higgs through other channels, but the cross sections were much lower. Those modes were secondary via $WW$ and $ZZ$ fusion [5]. The $Z$ in the $HZ$ production can be either virtual (LEP1 phase) or on mass shell (LEP2 phase) [5]. Combined results were from center of mass energy $\sqrt{s} = 65$ GeV to 209 GeV.

There were four decay modes that were particularly interesting for their distinctions [5]:

(a) Final products are all quarks:

$$H \rightarrow b\bar{b}, \quad Z \rightarrow q\bar{q},$$

(b) Final products are quarks and tau leptons:

$$\begin{cases} 
  H \rightarrow \tau^+\tau^-, & Z \rightarrow q\bar{q}, \\
  H \rightarrow b\bar{b}, & Z \rightarrow \tau^+\tau^-,
\end{cases}$$

(c) Final products are quark and neutrino pairs:

$$H \rightarrow b\bar{b}, \quad Z \rightarrow \nu\bar{\nu},$$

(d) Final products are light leptons and quarks:

$$H \rightarrow b\bar{b}, \quad Z \rightarrow \ell^+\ell^-,$$

where $q\bar{q}$ denotes a quark–anti-quark pair, $\nu$ is a neutrino regardless of generation, and $\ell^\pm \in \{e^\pm, \mu^\pm\}$. LEP1 only used modes (c) and (d), while the LEP2 phase included all four of them.

LEP at the time had four collaborations working on trying to find Higgs: ALEPH, DELPHI, OPAL and L3. ALEPH found an excess of $\sim 3\sigma$, suggesting Higgs boson with mass $M_H \sim 115$ GeV [5]. Other experiments, however, couldn’t confirm it, but then again, they couldn’t reject it at the 95% confidence level (CL). Using this data they excluded existence of SM Higgs boson below 114.4 GeV at 95% CL, comparing data with theoretically calculated BRs (fig. 5).

SM Higgs boson was also sought indirectly from fits to electroweak observables [5] (masses of $M_Z$ and $M_W$ depend on $M_H$ through loop-order corrections [5]). Thus they obtained the upper limit for the Higgs boson mass and at 95% CL constrained it to be in the $114.4$ GeV $< M_H < 186$ GeV range\textsuperscript{18}, which coincides with theoretical predictions for metastable electroweak vacuum (tab. 1).

\textsuperscript{17}Operated from 1989 to 2000.

\textsuperscript{18}Accumulated data of this indirect measurements over the last 20 years at LEP, SLC, Tevatron and elsewhere gave $M_H = 87^{+43}_{-26}$ GeV and $M_H < 157$ GeV at 95% CL.
4.2 Tevatron

Just like there is CERN in Europe, there is Fermilab in the USA. The LHC counterpart is called Tevatron, a \( p\bar{p} \) collider with much smaller circumference and for a change above the ground. Unfortunately the USA government stopped it’s funding in the September of 2011, which forced Fermilab to close down the collider. The data, however, is currently still pending analysis and so far we’ve been only fed the preliminary report.

Two collaborations were working on the experiment: CDF and DØ. Higgs boson production modes for Tevatron collisions are depicted in the figure below (fig. 6).

\[
\begin{align*}
\sigma \text{[fb]} & \quad \text{SM Higgs production} \\
10^{-3} & \quad \text{gg → h} \\
10^{-2} & \quad \text{qq → Wh} \\
10 & \quad \text{qq → Zh} \\
10^0 & \quad \text{gg, qq → tth} \\
10^1 & \quad \text{qq → qth} \\
10^2 & \quad \text{bb → h} \\
10^3 & \quad \text{qq → qqh} \\
10^4 & \quad \text{m_h [GeV]} \\
100 & \quad \text{TeV II} \\
120 & \quad \text{TeV} \\
140 & \quad \text{TeV} \\
160 & \quad \text{TeV} \\
180 & \quad \text{TeV} \\
200 & \quad \text{TeV} \\
\end{align*}
\]

**Figure 6** – Tevatron SM Higgs boson production cross sections. Computed by the TeV4LHC working group [7], for \( p\bar{p} \) collisions at \( \sqrt{s} = 1.96 \text{ TeV} \)

Fig. 6 shows that the most promising channels are gluon fusion and production with vector bosons \( Z, W^\pm \). QCD effects give greater background and uncertainties are greater than at LEP. They tried to get rid of background using auxiliary measurements and then Monte Carlo simulations for each specific channel in order to have as high background estimation as possible. For clarification and easier visualization see the Higgs boson branching ratios (fig. 5).

The “bread and butter” production channel was the aforementioned weak gauge boson fusion, through which they obtained most results. They used almost the same decay channels as the LHC experiments, so no use mentioning them again.

The collisions were finally made at the beam energy of \( \sqrt{s} = 1.96 \text{ TeV} \). With 95% CL they excluded two mass regions: \( 100 < M_H < 106 \text{ GeV} \) and \( 147 < M_H < 179 \text{ GeV} \). They also expect to exclude regions \( 100 < M_H < 119 \text{ GeV} \) and \( 141 < M_H < 184 \text{ GeV} \). The greatest reported discrepancy between SM and experiment was a 2.2 \( \sigma \) deviation at the mass \( M_H = 120 \text{ GeV} \) [9].

5 Latest Higgs boson search results

There are two experiments at the LHC which joined the Higgs hunt: ATLAS and CMS.
Cross section per each channel has been calculated by the LHC Higgs Cross Section Working Group [8]. Graphs per channel are depicted below (fig. 7).

\[ \sigma \times BR \text{ [pb]} \]

\( \sqrt{s} = 7 \text{ TeV} \)

**Figure 7** – Cross sections for each channel at \( \sqrt{s} = 7 \text{ TeV} \). This plots combine the cross sections with branching ratio, thus giving the total individual channel cross section.

The plot below shows combined exclusions by Tevatron DØand CDF compared to latest LHC exclusion zones.

\[ 95\% \text{ CL Limit/SM} \]

**Figure 8** – Latest exclusion plots given by [9]. They are from Tevatron report from March 16, 2012.

The CMS collaboration reported it’s largest excess (local significance of 3.1 \( \sigma \)) is reported at \( M_H = 124\text{GeV} \) [10]. The ATLAS collaboration reported largest excess at 126 GeV (local significance 3.6 \( \sigma \)). When uncertainties of ATLAS are taken into account this significance drops to 2.5 \( \sigma \) [11] and for CMS to 1.5 \( \sigma \).
High mass Higgs bosons weren’t excluded yet. For CMS they have been excluded in the 127-600 GeV mass range at 95%CL [10] and for ATLAS in the 131-238 GeV and then in the range of 251-466 GeV mass range at the same CL [11].

In any case, low mass Higgs boson is preferred (and for now more probable). Looking at the fig. 8 it also seems that we are gaining on the Higgs boson. The question of the Higgs boson existence will most likely be resolved within this or the next year.

6 Conclusion

Now you may ask yourself: how will the Higgs discovery affect me? How will this reflect on our daily lives? If the so called “God particle” will be excluded, will this mean the end of the world? Well, regardless of the outcome, nothing will change. In the best case scenario, some Nobel prizes will be awarded to the top brass and that’s it. There is no bigger mystery behind it apart from that the media created. These experiments serve only to round up the Standard Model and the electroweak theory. Even if in the Higgs boson will be excluded, many technological breakthroughs had to be made in other engineering sciences for the construction of such complex experiments so regardless of the outcome, we are gaining something.

The Higgs boson mass has been narrowed down experimentally to $115 < M_H < 127$ (CMS) $< 131$ (ATLAS) GeV, with $\approx 4.7 \text{ fb}^{-1}$ of data (integrated luminosity). After this year LHC will shut down for a longer period and resume in two years, hopefully with it’s design $\sqrt{s}$ and luminosity (this year the collisions are at $\sqrt{s} = 8 \text{ TeV}$). During this shutdown, there is enough data waiting to be analyzed.
References


