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Electroweak Symmetry Breaking. Higgs Particle Discovery Potential within the ATLAS Experiment

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Abstract. One of the most important questions in particle physics is the nature of electroweak symmetry breaking. This issue is one of the essential considerations in Standard Model (SM), which is yet, the most successfully developed theory to explain the physics of the fundamental particles and their interaction. The issue of the origin of the masses of the gauge bosons mediating weak interaction is one of the most important unanswered questions of the Standard Model. Currently, it is widely believed that this question can be answered by invoking the Higgs mechanism, which requires the onset of *spontaneous symmetry breaking* of the local gauge symmetry and provides a mass generation mechanism for both of the SU(2) weak gauge bosons and the observed massive quarks and leptons. It also predicts the existence of a massive scalar particle known as Higgs boson. The best experimental verification of the existence of the Higgs Mechanism would be the discovery of its physically detectable manifestation, the Higgs boson. One of the main physical goals of the experiment at the LHC is the search for the Higgs Particles. Over a large fraction of the mass range the discovery of the Standard Model Higgs boson will be possible in two or more independent channels. It has been also shown that, if discovered important Higgs boson parameters like the mass and the width can be measured. Together with measurements of the production rates and some couplings and branching ratios they will provide useful constraints on the Higgs couplings to fermions and bosons which in turn can be used to test the Standard Model predictions.

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1. Standard Model

One of the most important questions in particle physics is the nature of electroweak symmetry breaking. This issue is one of the essential considerations in the Standard Model (SM), which is yet, the most successfully developed theory to explain the physics of the fundamental particles and their interaction. The current Standard Model is built on the success of three previous theories.
The first is Quantum Electrodynamics (QED), the theory which describes the electromagnetic (EM) interaction in terms of underlying U(1) gauge symmetry. The next one, underlying SM, is the electroweak interaction theory guided by SU(2)×U(1) symmetry, first proposed by Glashow, Weinberg and Salam. This theory incorporates the successful QED model and provides a description of the weak force in terms of the exchange of massive vector bosons. The third theory which makes up the Standard model is Quantum Chromodynamics(QCD), guided by SU(3) symmetry. This quantum field theory describes the interaction of quarks through the strong 'color' field.

1.1 U(1) Gauge Symmetry & QED

The notion of U(1) gauge symmetry is that the transformation

$$\psi(x) \to e^{i\alpha(x)}\psi(x) \tag{1.1}$$

where, $\alpha(x)$ is the gauge parameter, must leave the Lagrangian of the theory invariant. To comply with this condition we need to introduce the concept of covariant derivative

$$D_\mu = \partial_\mu - ieA_\mu \tag{1.2}$$

which transforms exactly the same way as do the fields under consideration:

$$D_\mu\psi \to e^{i\alpha(x)}D_\mu\psi \tag{1.3}$$

Now, the bottom line is that demanding the local phase invariance we are forced to introduce a vector field A_μ, called the gauge field, which couples to Dirac particle (charge -e) and represent nothing else, but the physical photon field. Clearly , one needs this new field, since changing the phase locally will create a phase difference which would be observable if not compensated in some way.

Adding to the Lagrangian of the theory also the corresponding kinetic term. The latter will lead to the Lagrangian of QED

$$L = \overline{\psi}(i\gamma^\mu\partial_\mu - m)\psi + e\overline{\psi}\gamma^\mu A_\mu\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \tag{1.4}$$

Now, note that the addition of $\frac{1}{2}m^2 A_\mu A^\mu$ is prohibited by gauge invariance. The gauge particle photon must be massless.

1.2 Weak Interactions

The latter observation raises a serious problem if there is an attempt to apply the same ideas for the case of weak interactions. The major problem here is that the mediators of weak interactions $\left(W^{\pm}, Z_0\right)$ are observed to have masses on the order of $100GeV$. Note here that we cannot add terms describing masses of these gauge bosons since they violate gauge invariance. The ultimate reason which makes us respect the gauge symmetry is that otherwise we will encounter unrenormalizable divergences which makes this theory meaningless.

The latter issue of the origin of the masses of the gauge bosons mediating weak interaction is one of the most important unanswered questions of the Standard Model . Currently, it is widely believed that this question can be answered by invoking the Higgs mechanism , which requires the onset of *spontaneous symmetry breaking* of the local gauge symmetry and provides a mass generation mechanism for both of the SU(2) weak gauge bosons and the observed massive quarks and leptons. It also predicts the existence of a massive scalar particle known as Higgs boson. The best experimental verification of the existence of the Higgs Mechanism would be the discovery of its physically detectable manifestation, the Higgs boson.

2. Spontaneous Symmetry Breaking

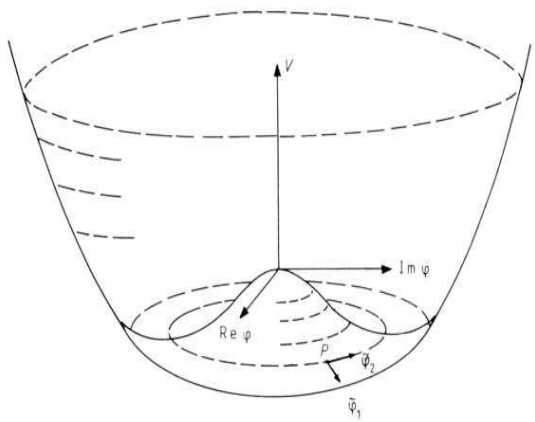
Before going into more rigor formalism of the notion of spontaneous symmetry breaking and Higgs mechanism let us give the following simple example of spontaneous symmetry breaking which is rather intuitive though. Consider a knitting needle and compress it with force F along its axis, the obvious solution is that it stays in the vertical configuration. However, if the force gets too large the needle will jump into a bent position. It does this because the energy in this state is lower than in the metastable state, where it stays aligned along the vertical axis. The cylindrical symmetry of the system around the vertical axis is apparently broken by the buckling of the needle. But the needle can buckle in any direction in the horizontal plane reaching a ground state with the same energy, so it is not possible to predict which way it will go.

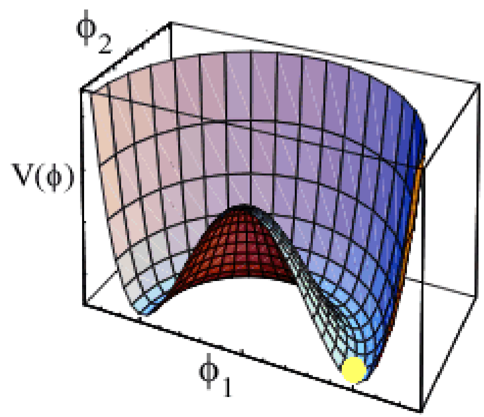
2.1 The Higgs Mechanism

Now, let us present more formal discussion of the generation of the mass for the gauge bosons by spontaneous symmetry breaking, as opposed to putting it in by hand. As an example consider the Lagranguian for the complex scalar field.

$$L = (\partial_\mu \phi^*)(\partial_\mu \phi) - \mu^2 \phi^* \phi - \lambda(\phi^* \phi)^2 \tag{1.5}$$

which is apparently invariant under global U(1) phase transformation. We will assume that $\lambda > 0$ and $\mu^2 < 0$.





Reexpress the Lagrangian in the form

$$L = \frac{1}{2}(\partial_\mu \phi_1)^2 + \frac{1}{2}(\partial_\mu \phi_2)^2 - \frac{1}{2}\mu^2(\phi_1^2 + \phi_2^2) - \frac{1}{4}\lambda(\phi_1^2 + \phi_2^2)^2 \tag{1.6}$$

Now it is obvoius that the minimum of the potential energy corresponds to the circle of radius v, such that

$$\phi_1^2 + \phi_2^2 = v^2 \quad \text{with} \quad v^2 = -\frac{\mu^2}{\lambda} \tag{1.7}$$

We translate the field ϕ to minimum energy position, which without loss of generality can be taken as point $\phi_1 = v$, $\phi_2 = 0$. We expand L about the vacuum in terms of fields η and ξ by substituting

$$\phi(x) = \sqrt{\frac{1}{2}}\left[v + \eta(x) + i\xi(x)\right] \tag{1.8}$$

into (1.11) and obtain

$$L' = \frac{1}{2}(\partial_\mu \xi)^2 + \frac{1}{2}(\partial_\mu \eta)^2 + \mu^2\eta^2 + cont \,\&\, cubic\_terms \tag{1.9}$$

The third term has the form of a mass term $-\frac{1}{2}m_\eta^2\eta^2$ for the η-field. Thus, the η mass is $m_\eta = \sqrt{-2\mu^2}$. The first term in L' represents the kinetic energy of the ξ-field, but there is no corresponding mass term for ξ. That is, the theory contains also the massless scalar , which is known as Goldstone boson. Thus, we have encountered a problem in attempting to generate a massive gauge boson, we see that a spontaneously broken gauge theory appears to be troubled with its own massless scalar particle. The potential in the tangent direction ξ is flat, implying a massless mode, putting in other words there is no resistance to excitation along the ξ direction. This is a simple example of the Goldstone theorem which states that massless scalars occur whenever a continuous symmetry of physical system is spontaneously broken. In the ferromagnet example discussed in class the analogue of the Goldstone boson is the long-range spin waves which are oscillations of the spin alignment.

To summarize, we note that the particle spectrum of L' appears to be a massless Goldstone ξ, a massive scalar η, and more crucially a massive vector A_μ. More precisely from the expression for L' we can read off

$$m_\xi = 0, \quad m_\eta = \sqrt{2\lambda v^2}, \quad m_A = ev \tag{1.10}$$

We have dynamically generated a mass for the gauge field, but we still have the problem of the occurrence of the massless Goldstone boson.

However, there is a crucial thing to note. By giving mass to A_μ, we have clearly raised the polarization degrees of freedom from two to three, because it can now have longitudinal polarization. Physically this is something that should not occur since simple translation of field variables should not create a new degree of freedom. The implication is that not all the fields presented in L' correspond to distinct physical particles. In order to understand which of the fields is unphysical we need to make use of our freedom of gauge transformation so that we can eliminate the “unphysical” field from the Lagrangian by means of going into a suitable gauge.

Let us substitute a different set of real fields h, θ, A_μ, where

$$\begin{aligned} \phi &\to \sqrt{\frac{1}{2}}(v + h(x))e^{i\theta(x)/v} \\ A_\mu &\to A_\mu + \frac{1}{ev}\partial_\mu \theta \end{aligned} \tag{1.11}$$

into the expression of the Lagrangian. We intentionally chose $\theta(x)$ so that field $h(x)$ is real. Upon the latter substitution one will come up with

$$L'' = \frac{1}{2}(\partial_\eta h)^2 - \lambda v^2 h^2 + \frac{1}{2}e^2 v^2 A_\mu^2 - \lambda v h^3 - \frac{1}{4}\lambda v h^4 + \frac{1}{2}e^2 A_\mu^2 h^2 + v e^2 A_\mu^2 h - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \tag{1.12}$$

The Goldstone boson actually does not appear in the theory. That is, the apparent extra degree of freedom is spurious, because it corresponds only to the freedom to make a gauge transformation. The Lagrangian describes just two interacting massive particles, a vector gauge boson A_μ and a massive scalar h, which is called a *Higgs particle*. The unwanted massless goldstone boson has been turned into the badly needed longitudinal polarization of the massive gauge particle. This is called the **'Higgs Mechanism'**.

2.2 Electroweak Symmetry Breaking

Finally, let us formulate the Higgs mechanism so that the $W^\pm$ and Z_0 become massive and photon remains massless. For that start off with the following, SU(2)×U(1) gauge invariant Lagrangian

$$L = \left| \left(i\partial_\mu - gT \cdot W_\mu - g' \frac{Y}{2} B_\mu \right) \phi \right|^2 - V(\phi) \tag{1.13}$$

where the ϕ_i are real scalar fields which belong to SU(2)×U(1) multiplets.

Arrange the fields as follows:

$$\phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} \quad \text{with} \quad \begin{matrix} \phi^\dagger = (\phi_1 + i\phi_2)/\sqrt{2} \\ \phi^0 = (\phi_3 + i\phi_4)/\sqrt{2} \end{matrix} \tag{1.14}$$

Now, to generate gauge boson masses we introduce Higgs potential $V(\phi)$ with $\mu^2 < 0$, and $\lambda > 0$. Choose the vacuum state to be

$$\phi_0 = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (1.15)$$

To identify the boson masses substitute (1.15) into the expression for Lagrangian (1.13). The term of interest will then be:

$$
\begin{aligned}
&\left|\left(-ig\frac{\tau}{2}\bullet W_\mu - i\frac{g'}{2}B_\mu\right)\phi\right|^2 \\
&=\frac{1}{8}\left|\begin{pmatrix} gW_\mu^3 + g'B_\mu & g\left(W_\mu^1 - iW_\mu^2\right) \\ g\left(W_\mu^1 + iW_\mu^2\right) & -gW_\mu^3 + g'B_\mu \end{pmatrix}\begin{pmatrix} 0 \\ v \end{pmatrix}\right|^2 \\
&=\frac{1}{8}\left[\left(W_\mu^1\right)^2 + \left(W_\mu^2\right)^2\right] + \frac{1}{8}v^2\left(g'B_\mu - gW_\mu^3\right)\left(g'B^\mu - gW^{3\mu}\right) \\
&=\left(\frac{1}{2}vg\right)^2 W_\mu^+ W^{-\mu} + \frac{1}{8}v^2\left(W_\mu^3, B_\mu\right)\begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix}\begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix}
\end{aligned}
\tag{1.16}
$$

where we took into account the fact that $W^\pm = \left(W^1 \mp iW^2\right)/\sqrt{2}$. Upon the comparison of the first term with the mass term expected for charged gauge boson $M_W W^+ W^-$ we have

$$
M_W = \frac{1}{2}vg \tag{1.17}
$$

The remaining term is off diagonal.

$$
\begin{aligned}
&\frac{1}{8}\left[g^2\left(W_\mu^3\right)^2 - 2gg'W_\mu^3 B^\mu + g'^2 B_\mu^2\right] = \frac{1}{8}v^2\left[gW_\mu^3 - g'B_\mu\right] \\
&+O\left[g'W_\mu^3 + gB_\mu\right]^2
\end{aligned}
\tag{1.18}
$$

Transform into basis of physical fields Z_μ and A_μ to diagonalize the mass matrix so that (1.18) must be identified with

$$
\frac{1}{2}M_Z^2 Z_\mu^2 + \frac{1}{2}M_A^2 A_\mu^2 \tag{1.19}
$$

Then, on normalization we have

$$
\begin{aligned}
A_\mu &= \frac{g'W_\mu^3 + gB_\mu}{\sqrt{g^2 + g'^2}} \\
Z_\mu &= \frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2 + g'^2}}
\end{aligned}
\quad \text{with} \quad
\begin{aligned}
M_A &= 0 \\
M_Z &= \frac{1}{2}v\sqrt{g^2 + g'^2}
\end{aligned}
\tag{1.20}
$$

Reexpressing the results in the notation widely excepted in HEP community

$$\frac{g'}{g} = \tan\theta_W \tag{1.21}$$

Therefore,

$$\begin{aligned} A_\mu &= \cos\theta_W B_\mu + \sin\theta_W W_\mu^3 \\ Z_\mu &= -\sin\theta_W B_\mu + \cos\theta_W W_\mu^3 \end{aligned} \tag{1.22}$$

So that we arrive at

$$\frac{M_W}{M_Z} = \cos\theta_W \tag{1.23}$$

One can show that within the Weinberg-Salam model

$$\begin{aligned} M_W &= \frac{37.3}{\sin\theta_W} GeV \\ M_Z &= \frac{74.6}{\sin 2\theta_W} GeV \end{aligned} \tag{1.24}$$

The experimental discovery of the W and z bosons have been made at CERN in 1983 in $\bar{p}p$ collider.
Experimental data suggest the following estimates for the W and Z boson masses

$$\begin{aligned} M_W &= 81 \pm 2GeV \\ M_Z &= 93 \pm 2GeV \end{aligned} \tag{1.25}$$

Summarizing we saw that the Higgs mechanism has made it possible to avoid massless particles. The basic problem is not just to generate masses, but to incorporate the mass of the weak boson while still preserving the renormalizability of the theory. Generically, there is nothing to prevent us from brutally breaking the gauge symmetry by inserting explicit gauge mass terms into Lagrangian, but the resulting theory losses all predictive power. In a spontaneously broken gauge theory, the symmetry is in a sense still present it is merely hidden by our choice of ground state.

3. Discovery potential of the ATLAS detector for the Higgs boson.

One of the main physical goals of the experiment at LHC is the discovery of the mechanism responsible for the electroweak symmetry breaking. The experimental observation of one or several Higgs bosons will be fundamental for better understanding of the electroweak symmetry-breaking mechanism.

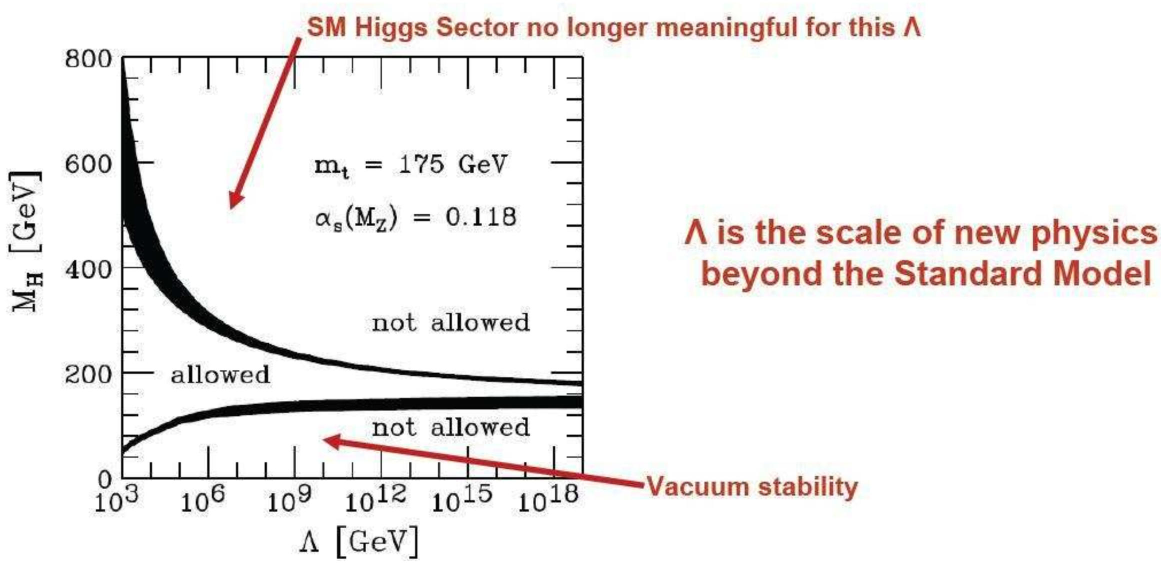
The Higgs boson mass is not theoretically predicted. From unitarity arguments an upper limit of ~1 TeV can be derived. The requirements of the stability of the electroweak vacuum and the perturbative validity of the Standard Model allows to set upper and lower bounds depending on the cutoff value chosen for the energy scale Λ up to which the Standard Model is assumed to be valid. Such analysis exist at he two-loop level for both low and upper Higgs mass bounds. If the cutoff value is chosen at the Planck mass, which means that no new physics appears up to that scale, the Higgs-boson mass is required to be in the range $130 < M_H < 180$ GeV. Experimentally, constraints on the Standard Model Higgs-boson mass are derived directly from searches at LEP, which lead to $M_H > 114.4 GeV$.

- If SM is valid up to the plank scale ~10^{19} GeV then M_H is in a limited range:

$$130 \text{ GeV}/c^2 \lesssim M_H \lesssim 180 \text{ GeV}/c^2$$

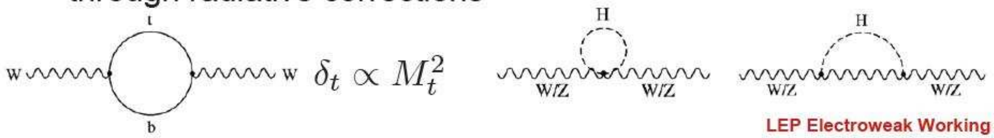
- If there is new physics ~1 TeV:

$$50 \text{ GeV}/c^2 \lesssim M_H \lesssim 800 \text{ GeV}/c^2$$

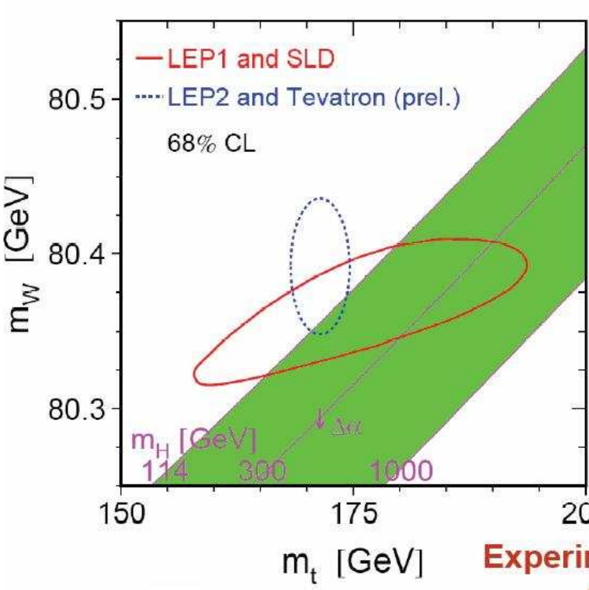


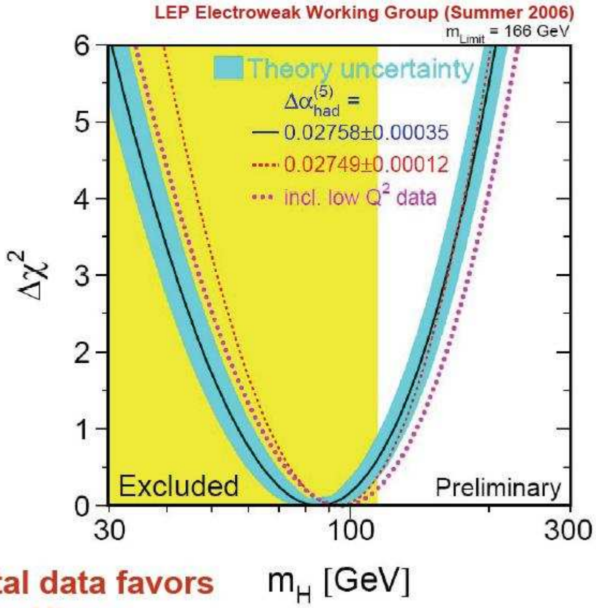
In supersymmetric theories, the Higgs sector is extended to contain at least two doublets of scalar fields. In the minimal version, the so-called MSSM mode, there are five physical Higgs particles: two CP-even Higgs bosons h and H, one CP-odd Higgs boson A, and two charged Higgs bosons $H^{\pm}$. Two parameters, which are generally chosen to be M_A and $\tan\beta$, the ratio between the vacuum expectation value of the two Higgs doublets, determine the structure of the Higgs sector at tree level. However, large radiative corrections affect the Higgs masses and couplings. The lightest neutral scalar Higgs boson mass, M_H, is theoretically constrained to be smaller that ~ $150 GeV$.

- Precision Electroweak measurements are indirectly sensitive to the Higgs mass through radiative corrections



$\delta_t \propto M_t^2$ $\qquad$ $\delta_H \propto \ln(\frac{M_H}{M_W})$

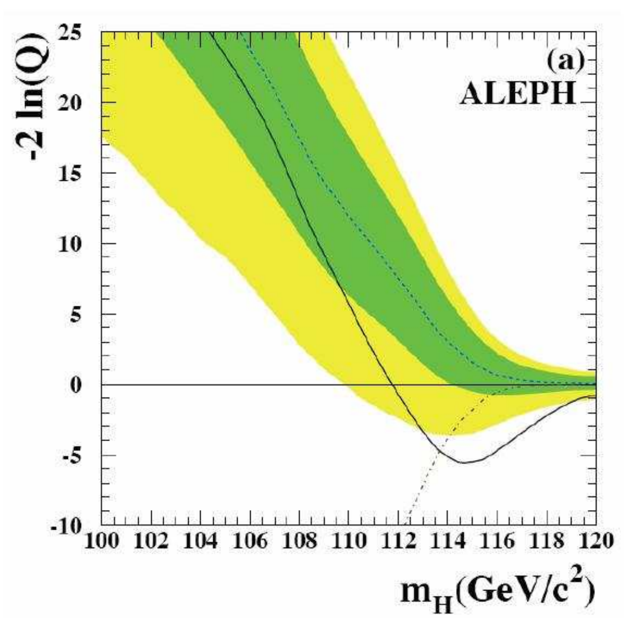


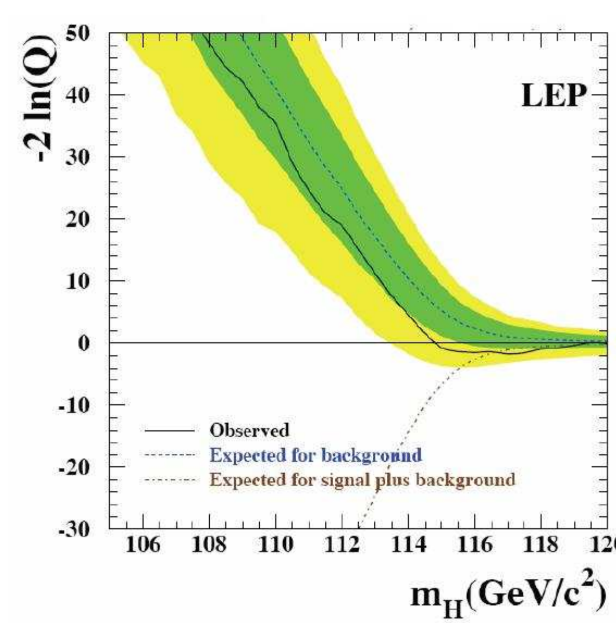


Experimental data favors a light Higgs

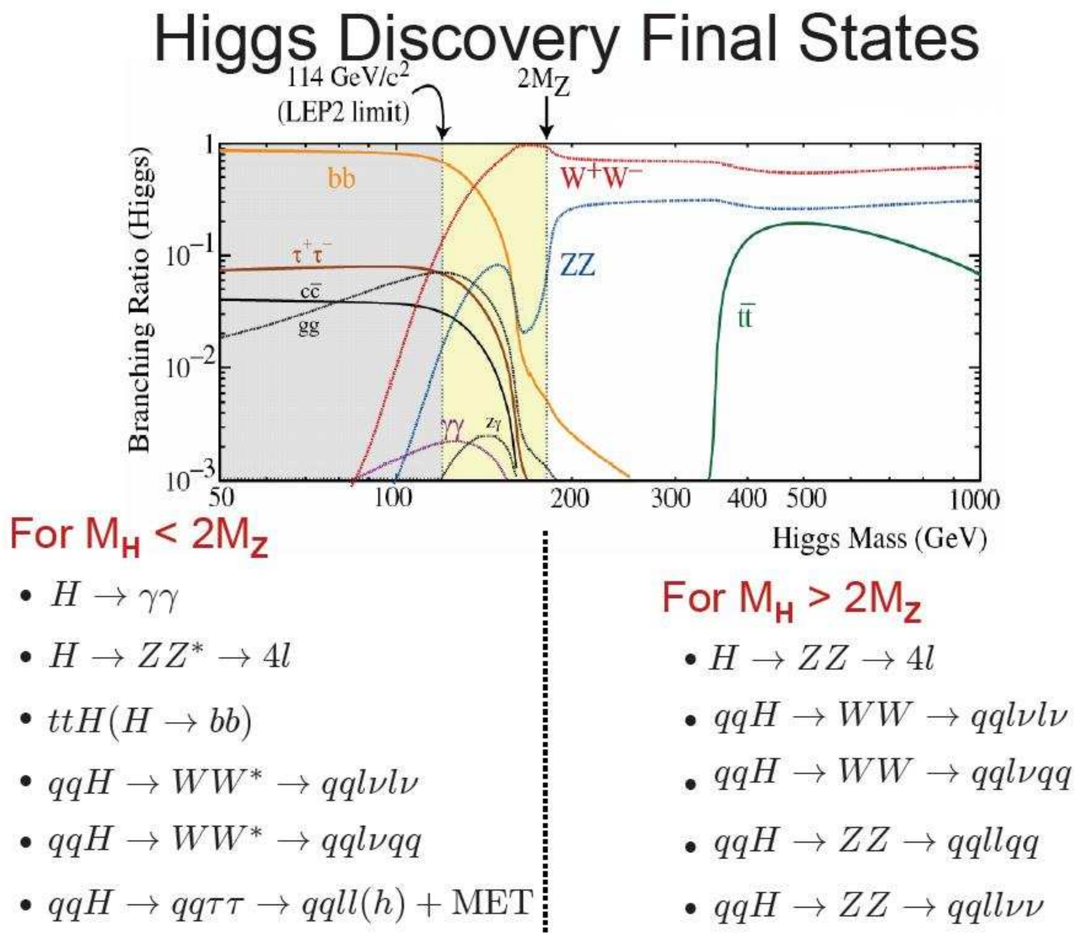
- Present limit from direct searches performed at LEP

$$M_H > 114.4\ \mathrm{GeV/c^2}, \mathrm{CL} = 95\%$$





Let us present the performance of the ATLAS detector in search for the Standard Model Higgs boson and for signals of electroweak symmetry breaking summarized in the following plots.



Over a large fraction of the mass range the discovery of the Standard Model Higgs boson will be possible in two or more independent channels. It has been also shown that, if discovered important Higgs boson parameters like the mass and the width can be measured. Together with measurements of the production rates and some couplings and branching ratios they will provide useful constraints on the Higgs couplings to fermions and bosons which in turn can be used to test the Standard Model predictions.

In the absence of scalar Higgs boson, the principal probe for the mechanism of electroweak symmetry breaking will be gauge boson scattering at high energies. It has been shown that ATLAS will be sensitive to presence of resonances, such as in the *WZ* system, up to masses around1.5TeV. Nonresonant processes, such as in the W^+W^+ production, will require a few years of high luminosity running and good understanding of the underlying backgrounds.

4. Conclusions

The official commissioning of the LHC and ATLAS experiment starts Fall 2007, when a large range of physics opportunities arise, among which are the origin of mass at the electroweak scale, possible access to Supersymmetric particles, solution to the riddle of antimatter and many others.
Nature has given answers to all of these problems long ago and it is just up to us to find out what the reality is. Currently we are armed with a powerful theory, corroborated with a number of experimental results, which also provides us with predictions to investigate at the LHC, leaving the major conclusions up to the future.
Most importantly though, as history has shown, the greatest advances in science are often unexpected. Although there is a deep understanding of what we hope to find at the LHC, nature may well have surprises in store. One thing is certain, the LHC will change our view of the Universe.

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