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Broken Symmetries and the Higgs Boson

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Abstract. The 40 years old Standard Model, the theory of particle physics, seems to describe all experimental data very well. The theory is based on symmetries, some of them are broken, mostly by the weak interaction. All of its elementary particles were identified and studied apart from the Higgs boson until 2012, when the two main experiments of the Large Hadron Collider at CERN, CMS and ATLAS observed a new particle with properties close to those predicted for the Higgs boson. The discovery of the Higgs boson proves the validity of the Brout-Englert-Higgs mechanism of spontaneous symmetry breaking and François Englert and Peter Higgs received the 2013 Nobel Prize in Physics. There are several questions yet concerning the possible theoretical significance of the mass of the new particle.

1 Broken Symmetries of the Standard Model

The Standard Model, the general theory of particle physics was established more than 40 years ago. It describes our world as consisting of two kinds of elementary (i.e. point-like, structureless) particles, fermions and bosons, differing by their spin, intrinsic angular momentum: fermions have half-integer, bosons have integer spins measured in units of $\hbar$, the reduced Planck constant. The elementary fermions have three families, each consisting of one pair of quarks and one pair of leptons. All fermions have antiparticles of opposite charges. The leptons can propagate freely, but the quarks are confined in hadrons: they can only exist in bound states of three quarks, baryons (like the proton and neutron) or those of a quark and an antiquark, mesons (like the pion). Three antiquarks make antibaryons like the antiproton.

In the Standard Model the three basic particle interactions, the strong interaction holding the quarks in the nucleons and the nucleons in the atomic nucleus, the weak interaction, responsible for the decay of nuclei and of the neutron, and the well known electromagnetic interaction, are all derived from local gauge symmetries. A gauge symmetry (or invariance) is a freedom to define the coordinate system measuring the strength of an interaction, the best known example of which is the freedom to choose the potential zero of an electric field. A local gauge invariance is its modified form when the gauge is changing in space-time according to a known function. The three basic interactions are derived of local gauge symmetries, the strong one from local SU(3) and the electroweak from local U(1)⊗SU(2) gauge invariance with *spontaneous symmetry breaking*. All of them are mediated by elementary bosons: the strong nuclear force by 8 gluons, the weak interactions by the three heavy

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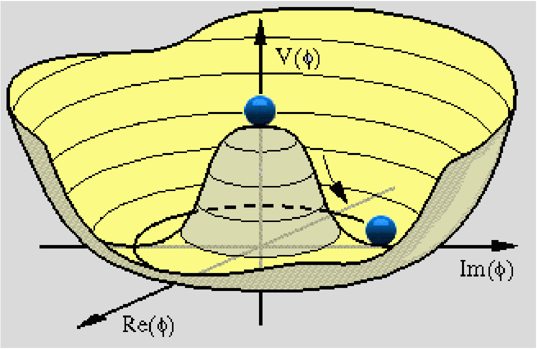

Figure 1. Spontaneous symmetry breaking: the BEH potential. The axial symmetry of the potential is not violated by putting a ball on the top at zero, but it will be spontaneously broken when the ball rolls down in the valley. However, the coordinate system can always be chosen so that the ball were at point $Im(\Phi) = 0$.

weak bosons and the electromagnetism by the photon. In order to cancel uncomfortable terms from equations the theory also needs the existence of an additional scalar boson, a particle with all its quantum numbers like charges and spin zero.

Local gauge symmetries give correct answers to important questions except the mass of elementary particles: one has to violate them in order to introduce their masses. This spontaneous symmetry breaking (SSB) was introduced in several steps to particle physics and it is now an integral part of the Standard Model. It was published in 1964 by several people independently,[1] but it is called BEH mechanism after Brout, Englert and Higgs, its first inventors.

It is remarkable what E. P. Wigner wrote[2] on gauge invariance: *In quantum theory, invariance principles permit even further reaching conclusions than in classical mechanics.....This gauge invariance is, of course, an artificial one, similar to that which we could obtain by introducing into our equations the location of a ghost. The equations must then be invariant with respect to changes of coordinates of that ghost. One does not see, in fact, what good the introduction of the coordinates of the ghost does.*

Broken (violated) symmetries play major roles in particle physics. According to Frank Wilczek[3] *".. the fundamental equations of physics have more symmetry than the actual physical world does."*. Steven Weinberg calls these symmetries *accidental*. The best known among them is parity which is maximally violated in weak interaction, but there is, e.g., the isospin symmetry, flavor-SU(2) and supersymmetry if it exists at all.

The BEH mechanism consists of adding to vacuum a potential which breaks its perfect symmetry. This is well illustrated by a Mexican hat (Fig. 1). Its axial symmetry is not violated by putting a ball on its top, however, the ball will eventually go down and break the original symmetry. The BEH potential, a complex doublet field, adds four degrees of freedom to the Standard Model: three are swallowed by the weak bosons and the fourth becomes a scalar particle, the Higgs boson, needed by the theory. The masses of the weak bosons are actually raised by the BEH mechanism whereas it just allows the appearance of the fermion mass terms in the electroweak Lagrangian. Thus the weak boson masses are predicted by the Standard Model, whereas the fermion masses are not, those are free, adjustable parameters. Note that the masses of our macroscopic world are mostly due to the energy content of the proton and the neutron and not due to the BEH mechanism.

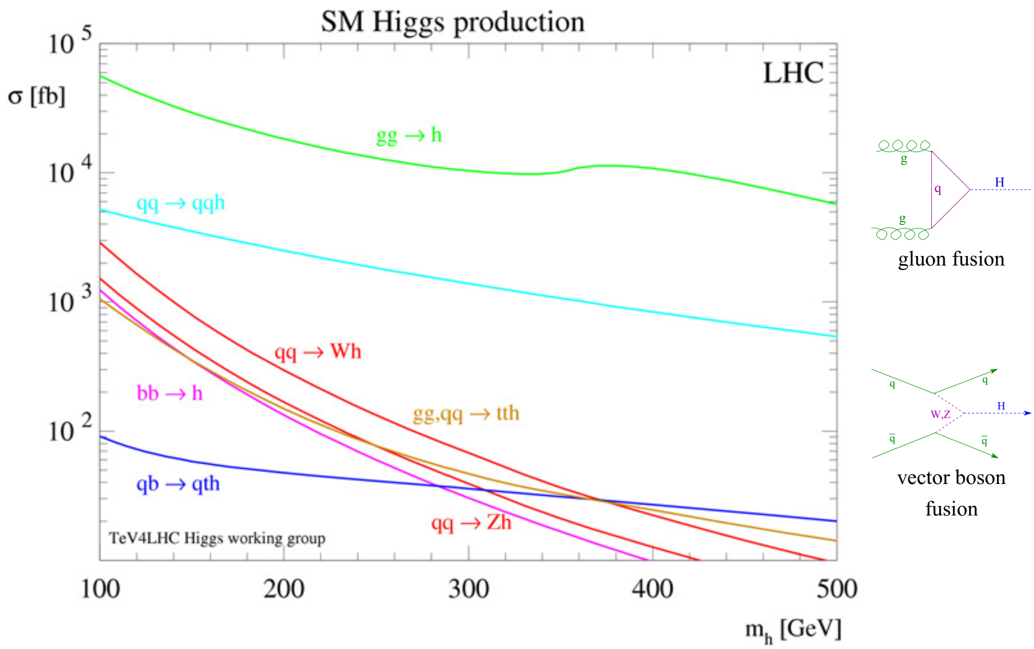

Figure 2. Formation of the SM Higgs boson in p-p collisions at LHC.

2 Search for the Higgs boson

The last 40 years more and more precise new data were acquired at the particle accelerators, predominantly at the electron-positron colliders and all seem to agree very well with the predictions of the Standard Model. However, the SSB mechanism could not be ascertained until the hypothetical scalar boson, the Higgs boson was not found.

The Higgs boson of the Standard Model is the only scalar particle: all of its quantum numbers are zero, its only property is mass. Fitting experimental data predicted that the Higgs mass had to be around 100 GeV (between 80 and 160 GeV within 95% confidence). All constituents of the Standard Model were identified and studied experimentally before the launch of the LHC, apart from the Higgs boson, that is how it became the most wanted particle. As Peter Higgs himself told[4] “It was in 1972 ... that my life as a boson really began”.

According to the general convention in accelerator experiments a given new phenomenon is excluded if we can show it not appearing at a $\geq 95\%$ confidence level and observed if it exceeds $> 5\sigma$ above background where σ is the experimental uncertainty according to the best honest guess of the experimentalist.

That σ uncertainty has a *statistical component* from the number of observed events and *systematic* ones from various sources, like Monte Carlo statistics and inputs, experimental calibration factors, detection efficiencies, etc, with the common name *nuisance parameters*. We derive the final uncertainty via marginalizing (integrating out)[5] the nuisance parameters Θ in likelihood $\mathcal{L}$ using the related probability distributions $\mathcal{W}$: $\mathcal{L}(P; x) = \mathcal{W}(x|P) = \int \mathcal{W}(x|P, \Theta)\mathcal{W}(\Theta|P)d\Theta$.

Another important feature of high-energy data analysis is the *blind analysis*.[6] It came from medical research and the idea is to optimize, prove and publish your analysis technique using simulations and earlier data only before touching new data in the critical region. For instance, in spring and early summer, the 2012 CMS data were blinded in the $110 < M_H < 140$ GeV (where M_H is the assumed Higgs mass) because of the 3σ excess observed in 2011. The same procedure was used again in autumn 2012. The methods had to be fixed and approved by the collaboration before simultaneous *unblinding* for all analysis channels.

What we usually try to observe is a resonance. For a particle with lifetime $\tau = \Gamma^{-1}$ and decay rate Γ the event rate against the invariant mass of the decay products is $|\chi(E)|^2 = \frac{1}{(E-M)^2+\Gamma^2/4}$, i.e. a Lorentz curve (Breit-Wigner resonance). It shows a peak at the M invariant mass of the decaying system with a full width at half maximum Γ. We claim the discovery of a new particle if we see a resonance at the invariant mass of the particle in all expected decay channels, by all related experiments.

The search involves several consecutive steps. First we compose a complete *Standard Model background* using Monte Carlo simulation taking into account all types of possible events normalized to their cross-sections, and *Higgs signals*, simulations of all possible production and decay processes with all possible Higgs-boson masses. All these go through the *detector simulation* to get events analogous to the expected measured ones. *The event selection* is optimized via reducing the B background and enhancing the S signal via maximizing e.g. $N_S / \sqrt{N_S + N_B}$ or $2 \cdot (\sqrt{N_S + N_B} - \sqrt{N_B})$[7] One then *checks the background*: the simulation should reproduce the observed background distributions in all details. For instance, you can check the background of the decay of a neutral particle to charged leptons by selecting lepton pairs of identical charges in data and in simulation.

Once we are happy with the simulations and the event selection, we must choose a test statistic. That could be any kind of probability variable characteristic of the given phenomenon: probabilities for having background only, signal only or their various combinations. One of the favorite is the Q likelihood ratio of signal + background over background: $Q = \mathcal{L}_{s+b}/\mathcal{L}_b$. As you see, although our basic approach is definitely frequentist there is a certain Bayesian influence as well.

Several other testing variables can be constructed on the same basis, the most frequently used ones are probabilities of NOT having the expected signal on the basis of the expected background and the collected data: CL_b, the signal confidence level assuming background only, i.e. the complete absence of the signal, or the so-called *p−value*: the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true. Translated to our language that means the probability that random fluctuations of the measured background could give the observed excess.

3 Exclusion at LEP

The rate of collecting data at particle colliders is called *luminosity*, that is similar to the *beam flux* in fixed-target experiments. It is defined as $L = fn\frac{N_1 N_2}{A}$ where f is the circulation frequency of the colliding beams; n the number of particle bunches in the ring; N_1, N_2 are the numbers of particles in the two kinds of bunches; A is the spatial overlap of the colliding bunches. The total number of collisions is characterized by the integrated luminosity: $\int_{t_1}^{t_2} Ldt$ which is usually measured in units of inverse cross-section, at LEP in [pb^{-1}] and at LHC in [fb^{-1}]. The expected rate of a reaction with cross section σ at ϵ detection efficiency is then $R = \epsilon\sigma L$.

Although the four large experiments at the Large Electron Positron (LEP) collider saw no new physics, no deviation from the Standard Model, LEP provided an incredible amount of very precise measurements. In its last two years of working, LEP was mostly devoted to the search for the Higgs boson, collecting more luminosity at higher energies than in the previous 10 years together.

At LEP the dominant formation process is *Higgs-strahlung* $e^-e^+ \to ZH$ (the name comes from the funny *English?* word Bremsstrahlung, other languages use translations of the German expression

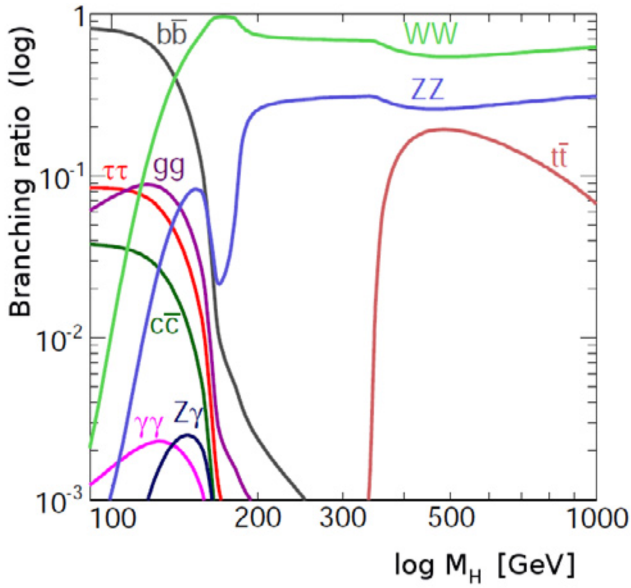

Figure 3. The various decay channels of the Higgs boson according to the Standard Model. Below 120 GeV the $H\to b\bar{b}$ decay channel dominates.

meaning *braking radiation*) and the dominant Higgs decay is to 2 b-quarks (Fig. 3). The various channels are different only due to the various decay processes of the accompanying Z boson.

LEP had four quite similar large experiments in the four interaction points of the electron-positron collider, ALEPH, DELPHI, L3 and OPAL (the present author was in OPAL). The structures of the large high-energy detectors are very similar, consisting of onion-like layers with huge magnets encompassing as much as possible of the detector parts. A sensitive pixel detector right around the beam pipe at the interaction point, a tracking system of multiwire chambers or semiconductor detectors of minimal weight material following the tracks of the particles in the magnetic field of the detector, then an electromagnetic calorimeter, something heavy absorbing all electrons and photons, outside of that an even heavier hadron calorimeter, absorbing the pions, protons, neutrons, etc., and finally, muon chambers, identifying the path of muons leaving the system.

Statistics played a rough joke at LEP: one of the experiments, ALEPH, saw a very significant signal corresponding to a Higgs boson of a mass of 115 GeV/c^2, while the rest of LEP did not see anything.[8] The signal was observed in one of the possible Higgs decay channels only and its reconstructed mass was critical as it coincided with the average kinematic limit of LEP: in 2000 the average collision energy of LEP was about 206 GeV and the observed resonance was found at 115 GeV/c^2: the difference was very close to the mass of the Z boson, 91 GeV/c^2 (see[9] for more details).

The ALEPH observation caused quite an excitement at LEP: many physicists signed the petition to the Director General of CERN to extend the life of LEP by another year, but that was refused: the simulated projections were not very promising for a discovery of the SM Higgs boson, and the contractors for building LHC were already prepared to start.

4 Observation at LHC

The design of LHC and its experiments started well before the actual start of LEP, which means that the construction of the LHC detectors took two decades of hard work before the actual data acquisition started. Its first two years LHC devoted to development rather than data taking, that really started in 2011 only.

Just like LEP had, the Large Hadron Collider has 4 beam-beam interaction points with a major experiment in each. The two largest ones, ATLAS and CMS have been designed with the main aim of discovering the Higgs boson. These collaborations are huge. According to the official statistics in 2012 CMS had 3275 physicists (including 1535 students) and 790 engineers and technicians from 179 institutions of 41 countries. The largest participant country was the USA, then Italy, Germany and Russia.

Figure 2 shows the various formation processes of the SM Higgs boson in p-p collisions at LHC. The dominant reaction is gluon fusion and vector boson fusion is also significant.

Even before LHC started the parameter fitting of the Standard Model pointed toward a light Higgs boson, with a mass around 100 GeV/c^2. As LEP excluded the Higgs boson below 114 GeV/c^2 the LHC experiments had to be prepared for detecting the Higgs boson in the most complicated mass region, around 120 GeV/c^2, with several competing decay channels. It was shown very early that the best channel to observe a light Higgs boson at LHC should be the decay to 2 photons because of the very high hadron background. Thus both large experiments, CMS and ATLAS designed their electromagnetic calorimeters with this in mind. The CMS one consists of 75,848 $PbWO_4$ single crystal scintillators, whereas the electromagnetic calorimeter ATLAS is a sampling one based on liquid argon shower detectors.

By the beginning of 2012, when all 2011 data were analyzed, the possible mass of the SM Higgs boson was already confined to the region of $114 < M_{\mathrm{H}} < 127$ GeV/c^2 by CMS[10] (with very similar results from ATLAS). In that region $2 \ldots 3\sigma$ excesses were found at ~125 GeV/c^2 in the two main decay channels, $\mathrm{H} \rightarrow \gamma\gamma$ and $\mathrm{H} \rightarrow \mathrm{ZZ}$. After reanalyzing their data the Tevatron experiments, CDF and D0 also found an excess at this mass (after the LHC started the Tevatron accelerator of Fermilab was stopped). It seemed more and more probable that the Higgs boson will be observed at LHC in 2012, it was even decided by the CERN administration to extend the data taking scheduled for 2012 before the long shutdown for accelerator development if necessary for the discovery.

July 4th, the beginning of the large annual high-energy physics congress in Melbourne, the spokespersons of ATLAS and CMS gave talks from CERN (in internet connection to the whole word, including, of course, the main auditorium of the Australian conference) on Higgs search. They announced that at LHC collision energies 7 and 8 TeV, in two decay channels $\mathrm{H} \rightarrow \gamma\gamma$ and $\mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow \ell^+\ell^-\ell^+\ell^-$, at an invariant mass of $m \approx 126$ GeV a new boson is seen at a convincing statistical significance of 5σ confidence level each with properties corresponding to those of the Standard Model Higgs boson. The fact that the new particle could decay to two photons or Z bosons, confined its spin to an even integer, i.e. a boson of $S = 0$ or $S = 2$. Of course, as the data analysis was optimized to find the SM Higgs, it was very unlikely to find something very different. Nevertheless, the two experiments emphasized that it has to be studied, whether or not its spin is really zero with a + parity (the pseudo-scalar mesons have spin 0 with negative parity), and whether its decay probabilities to various final states follow the predictions of the Standard Model.

5 Reactions of the Media

The saying that *three people can keep something secret only if two of them are dead* is attributed to Benjamin Franklin. As any result of a collaboration has to be approved by all members before it is

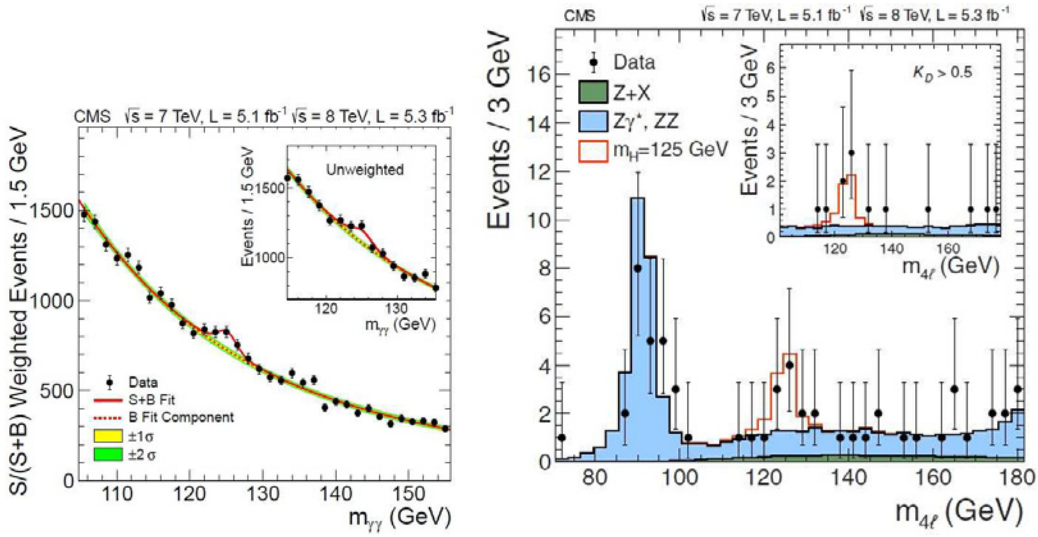

Figure 4. Observation[13] of the Higgs-like boson by CMS in (left) the $\gamma\gamma$ and (right) $\ell^+\ell^-\ell^+\ell^-$ invariant mass distribution at 125 GeV/c^2. The amplitudes of the observed signals are very close to the expectations of the Standard Model. The ATLAS spectra are similar.

made public, the more than 6000 participants of the two large experiments knew well in advance the developing result. Thus two days before the 4th July announcement, *Nature Online* already reported the result.[11] Of course, the fact that CERN invited to this seminar all leading scientists of the field including those who developed the mechanism of spontaneous symmetry breaking for the Standard Model also helped people to guess that something dramatic will be announced.

CERN produced some figures concerning the media echo of the day: 55 media organizations were represented at the talks of 4 July, the talks were broadcasted via close to half a million internet connections (many of them conference rooms in partner institutions, 1034 TV stations devoted 5016 news broadcasts to the event for more than a billion (10^9) people. Many-many news articles and even more blogs and talks discussed the conditions and importance of the discovery.

6 The observations

On 31 July the two experiments submitted papers of the discovery to Physics Letters B, they were published 14 August.[12,13] Both papers are 15 pages long followed by 16 pages of close to 3000 authors and both are dedicated to the memory of those participants who could not live to see the result of the more than two decades of construction work. Fig. 4 shows the di-photon and 4-lepton spectra obtained by CMS in 2012.

What was really convincing of the observation was the distribution of the p-values, the probabilities that the given event is due the random oscillation of the background and not due to the Higgs boson at the chosen mass value. It was a joke of statistics that in July 2012 adding together two decay channels, $H \to \gamma\gamma$ and $H \to 4\ell$ gave the same 5σ significance for both ATLAS and CMS whereas adding to it the WW channel increased the significance to 6σ for ATLAS and adding all channels together reduced it to 4.9σ for CMS.

7 Is it really the SM Higgs boson?

Analyzing all data collected in 2012 led to the conclusion that the observed properties of the newly discovered particle are within statistics close to those predicted for the Higgs boson of the Standard Model. The fact that it decays to two photons points to its having spin $S = 0$ or 2. The charged lepton spectra bears the features of its having $S = 0^+$.[15] Its mass as determined by CMS[16] by the average of all decay channels is $< M_X >= 125.7 \pm 0.3$(stat) $\pm$ 0.3(syst). The ATLAS result[16] is almost exactly the same: 125.5 ± 0.2(stat) ± 0.6(syst). The differences in the uncertainties are due to the facts that (i) ATLAS had more signal-like data, but (ii) got more different masses in the main channels. The signal strengths of the new particle are also compatible with that expected for the Standard Model Higgs boson: for CMS it is 20% less while for ATLAS 40% more than the SM prediction, but both differences are within the experimental uncertainties. As a theoretician remarked whenever ATLAS has an excess CMS comes up for everybody's annoyance with a deficit, bringing the average close to the SM prediction.

The LHC experiments studied the cross sections of the processes connected to the new particle. The signal strengths of production and decay in various possible channels of the Higgs-like boson measured by CMS[14,16] as compared to those predicted by the Standard Model for the Higgs boson with a mass of 125 GeV/c^2. The amplitudes of all observed signals are in agreement with the expectations of the Standard Model. ATLAS had similar results.

8 What next?

Thus what we found is very likely the Standard Model Higgs boson. On one hand this is a great success of particle physics. On the other hand this is somewhat of a disappointment as the SM has theoretical shortcomings which need new physics to resolve. Just to list a few of them: it cannot unite the interactions at large energies, cannot account for the dark matter of the Universe and cannot explain neutrino oscillations. There are many extensions of the theory which should result in deviations from the Standard Model. All those problems can be resolved e.g. by *supersymmetry*, but none of its predicted phenomena could be found yet experimentally. The observables of the Higgs boson should be sensitive to some of the features of new physics and these studies will be the main job of ATLAS and CMS in the future, from 2015 when the LHC will restart with almost twice the energy and luminosity of 2012.

It is very interesting that the 126 GeV mass of the Higgs boson seems to be exciting for theoreticians, there was even a special workshop[17] organized to discuss this mass in 2013. The reason is that $M_H = 126$ GeV is at the border line of the stability of electroweak vacuum on the plane of top mass against Higgs mass. At the Madrid workshop the apparent fine tuning of the Standard Model compelled some physicists to recall the anthropic principle.

9 Problems of the Standard Model

There are many theoretical problems with the Standard Model, although it seems to reproduce all experimental data very well. Just to list a few:

- It does not include gravity.
- It cannot explain the nature of dark matter and dark energy and the lack of antimatter in the Universe.
- It has an artificial ad-hoc mechanism of creating masses for the fermions and cannot explain the masses of the neutrinos.

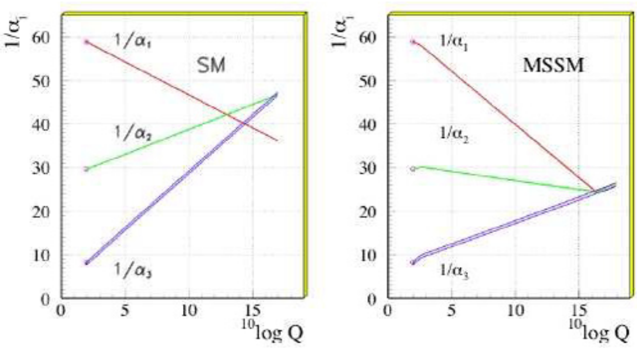

Figure 5. Energy dependence of the couplings of the three gauge interactions according to the Standard Model (left) and including the supersymmetric particles (right). Supersymmetry helps to unite the interactions.

- The fractional charges of the quarks is against the quantization of atomic and electron charges.
- The coupling constants of the three gauge interactions converge at high energies, but do not meet.
- How can a nucleon have exactly $J = \frac{1}{2}$ spin when it is full of gluons and virtual quark-antiquark pairs?
- Why there are 3 fermion families?
- Naturalness (hierarchy) problem: The mass of the Higgs boson quadratically diverges due to radiative corrections, but it is cancelled if fermions and bosons exist in pairs.

10 Supersymmetry

Most of these problems can be solved by extensions of the Standard Model, the most favored among them is *supersymmetry*. It assumes that fermions and bosons exist in identical pairs, with just their spins different. If it is valid at all, it is obviously broken at low energy, as we do not see those partners: if they exist they must be much heavier. There are also many-many alternative models, extensions of the Standard Model and we are searching for deviations from the SM predictions.

Supersymmetry can unify the gauge coupling constants (Fig. 5). It helps to include gravity and provides an excellent candidate for dark matter as the lightest supersymmetric particle (if its quantum number, the R parity is conserved) cannot decay further, just stays. This help the observation as well: supersymmetric particles can be produced in particle-antiparticle pairs at high-energy collisions and at the end of their decay chains the lightest one disappears as it is undetected leaving behind a great portion of unaccounted missing energy. As supersymmetry predicts 5 Higgs-bosons, the Higgs-sector is one of the most important ones to check whether or not it is valid.

The *Minimal Supersymmetric Standard Model* adds 105 parameters to the original 19 ones of the Standard Model. This is much too many, impossible to directly analyze. There were several very simplified versions, but those were eliminated by the early data of LHC already. Now the experimentalists are looking at key points for deviations from the predictions of the Standard Model and for that we need great amounts of very precise data.

Acknowledgments

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