THE STORIED TALE OF THE ELUSIVE HIGGS BOSON

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Abstract

Physicists of the last century formulated an elegant theory, guided by symmetries of particle interactions, that gave mathematical sense to quantum and relativistic laws at high energies. This theory postulated the existence of new particles which were discovered years after its formulation. It has been verified in thousands of measurements already made at particle accelerators.

However, a fundamental explanation of a basic observation remains mysterious. Why do most particles have a mass ? A cornerstone postulate of the theory states that mass is nothing else but energy given to an elementary particle permanently via a so far undiscovered force. This idea can be proven by discovering the so called" Higgs boson", which is the carrier particle of that force. Three accelerators, the LEP collider in Geneva which run in the 1990s, the Tevatron accelerator currently operating in Chicago, and the forthcoming Large Hadron Collider, are dedicated to this research, making the Higgs boson the most sought after particle in history.

The abstract form of quantum laws requires sophisticated mathematics in order to calculate quantitatively their experimental consequences. Such intricate computations at high energies are only possible using approximations which cannot be improved without breakthroughs in developing mathematical methods. Theoretical predictions based on first approximations for Higgs boson interactions are of especially poor precision.

We have been developing novel techniques for computing probabilities of particle reactions. With these methods, we can now predict accurately the number of Higgs bosons which may be produced and detected at accelerator experiments. This improved precision increases the sensitivity of experiments to potential Higgs boson signals and the level of confidence in setting exclusion limits on its mass using existing data. The same predictions will be crucial in interpreting any future discovery of the Higgs boson.

Plato believed that our senses perceive multiple manifestations of ideal objects whose true nature is understood with the use of intelligence. "*...although they make use of the visible forms and reason about them, they are thinking not of these, but of the ideals which they resemble… the forms which they draw or make, and which have shadows and reflections of their*

own, are converted by them into images, but they are really seeking to behold the things themselves, which can only be seen with the eye of the mind."

The quest to understand the inner workings of nature is everlasting. The ideals of Plato differ from the modern laws of physics, the principle of least action, the uncertainty principle, the axioms of the theory of relativity, and quantum field theory. However, the motivating curiosity which leads to new discoveries is common and human. In the last few centuries, this curiosity has been methodically satisfied in a progression of empirical observations, experimentation, and formal abstractions.

How much truth do physical laws behold ? A remarkably small number of equations, explains a plethora of diverse phenomena. Cosmological events which happened 10^9 light years away from the earth, and reactions which are completed 10^{24} times faster than an eye-blink, fit within a spartan system of a few principles.

1. Symmetry of particle interactions

Particle physicists of the last century developed a successful theory of how the basic constituents of matter interact at minute distances. At times, they were only guided by the symmetry and self-consistency of their equations. For these equations to make sense, bold predictions of elementary particles which were not yet discovered were necessary. The charm quark, the bottom quark, the W boson, the Z boson, and the top quark were found later one after the other at particle accelerator experiments. As a result, we have inherited a very beautiful theory of particle physics, the so called Standard Model of strong and electroweak interactions, which has passed thousands of tests in dedicated measurements of elementary particle reactions.

The mathematical structure of the theory counters naive physics intuition. The Standard Model unifies the electromagnetic force and the weak force. Its equations are formulated to be symmetric in the limit where all the carriers of the electroweak force (the photon, the W boson and the Z boson) have no mass, although only one of them, the photon, is a massless particle. In this unrealistic limit, one can exchange internal degrees of freedom of elementary particles in certain ways (symmetry transformations) without altering the relative strengths of electroweak interactions. If this symmetry was perfect, then elementary particles would experience additional long range forces which have not been observed in nature.

How such an apparently erroneous symmetry could be used to formulate a realistic theory of particle interactions ? As the speed of particles approaches the speed of light, their mass affects less the outcome of experimental measurements. It has been revealed at experiments with collisions of increasingly fast moving particles that their interactions become more symmetric. The results of such experiments agree with very precise predictions of the Standard Model. The symmetry of the Standard Model theory is therefore a true high energy symmetry of nature.

2. Mass of elementary particles

If the symmetry of the Standard Model is a fundamental law, why does it break at low energies and why elementary particles have a mass ? This question cannot be circumvented by implementing the mass of elementary particles axiomatically on a theory of electroweak interactions. Adding mass terms "by hand" to the equations, without devising an underlying mechanism, we arrive to calculations with illogical results. For example, we find that at high energies the probability of some particles to interact is larger than 1. To rescue the predictability of our physical laws, the mass of an electroweak elementary particle must be an emergent dynamical phenomenon.

Einstein gave a simple definition for the mass of a particle as the energy that it possesses when it is not moving. Are there any known dynamical mechanisms which generate energy at rest ? A known example is in particles which are not elementary. Particles with substructure make up almost the entirety of the physical world. The proton is a composite particle of two "up" and one "down" quark and the neutron consists of one "up" and two "down" quarks. The masses of the proton and the neutron are almost a thousand times larger than the masses of their quark constituents. The origin of the excess mass is nevertheless well understood ; it is due to the potential energy from the strong force which binds the three elementary quarks together.

Elementary particles appear to us as having no constituents. However, we believe that they are massive due to a similar reason as in composite particles : a force which provides them with energy at rest. Known forces, the electroweak and strongforce, cannot generate mass for the Z boson and the W boson without spoiling the calculability of probabilities for particle reactions at high energies. The mass of electroweak elementary particles must emerge due to a novel force, which has not yet shown any other experimental signals.

3. Quantum field theory

Modern physics unifies the notions of forces, particles and interactions within the theory of quantum fields. This is a theory which combines consistently quantum mechanics and Einstein's special relativity. According to quantum field theory, particles are discrete units of fields carrying quanta of conserved quantities such as energy, momentum, electric charge, and others. Particle interactions are described as changes of systems of particles as they evolve in time, due to their fields being coupled together. Fields are coupled when the time evolution of one field is affected by the presence of the others.

For example, many electromagnetic phenomena are explained with an electron and a photon field. Electron particles are quanta of the electron field. Light is made up of photon particles, which are quanta of the photon field. The electron and photon fields are coupled. As in Maxwell's classical theory of electromagnetism, a moving electron (electron field) can alter the magnetic (photon) field, and conversely, a magnetic field can change the motion of an electron. The electromagnetic force can be understood in quantum field theory as the macroscopic effect of the absorption or emission of photons from electrons or positrons (particle and anti-particle quanta of the electron field).

4. Spontaneous symmetry breaking

The Standard Model provides the simplest theoretical description for a new force which generates mass, by introducing the Higgs field. According to the model, fields of heavier particles are coupled stronger to the Higgs field. What is important for the Higgs field is that it can couple to itself. This self-interaction provides the Higgs field with a non-zero energy everywhere in space. The coupling of all other fields to the Higgs field, feeds their corresponding particles with a constant amount of energy too, even when they are at rest.

This mass generation mechanism in the Standard Model is known as spontaneous symmetry breaking. While all interactions are symmetric, the spectrum of elementary particles of the theory turns out to be non-symmetric. This mechanism leads to a prediction for the mass of the carriers of the weak force, the W and the Z boson. The ratio of their masses can be predicted by the strengths of their interaction with other electroweak particles. This prediction of the theory has been tested with very precise experimental measurements.

More complicated models than the Standard Models are of course plausible. Models beyond the Standard Model are different in various aspects of particle interactions at very high energies. Many of them provide more satisfactory explanations about the origin of the self-interaction of the Higgs field. However, forces and symmetries which they introduce lead to a similar spontaneous symmetry mechanism as in the Standard Model. We view the Standard Model as a common effective description of diverse possibilities for physics laws at very high energies.

5. The Higgs boson

According to the laws of quantum field theory, there must exist a new type of particle corresponding to quanta of the Higgs field. This particle is known as the Higgs boson. Such a particle has not yet been found, besides being the most sought after particle in the history of physics. The discovery of the Higgs boson will probably happen within this decade, and it will shed light to one of nature's best kept secrets : why elementary particles have mass.

The Higgs boson interacts feebly with the nearly massless electrons and the constituents of the proton, particles which we know how to accelerate and collide. For that reason the search for its signals is painstaking and long, relying on the most advanced technological knowledge in accelerator physics and gigantic international experiments. During the last three decades, particle physicists have searched with a realistic chance for finding direct evidence for signals of the Higgs boson in high energy particle collision experiments. The Large Electron Positron (LEP) collider searched for it until 2002 in Geneva.

Since then, the Tevatron accelerator in Chicago, has continued the search. The Large Hadron Collider (LHC), the accelerator experiment with the highest energy collisions in history, is anticipated to be able to either discover or exclude the Higgs boson with the properties predicted by the standard theory of elementary interactions.

We expect Higgs bosons to be produced in particle reactions at the Tevatron and the LHC rarely, radiated off other intermediate heavy particles, the top quark, the W boson and the Z boson, which are produced first. If the Standard Model is correct, up to about 10,000 Higgs bosons may have already been produced at the Tevatron. However, it has not yet been possible to establish that such reactions took indeed place. A Higgs boson is not a stable indestructible particle, and there is not enough time after it is produced to reach the detectors of accelerator experiments. In less than 10^{-22} seconds, a Higgs boson decays to other more stable particles such as electrons, photons, and others. This extremely short time is not even sufficient for a Higgs boson to travel a distance of a proton radius. Detectors at accelerator experiments are placed a few millimeters to several meters away from the interaction center.

A major difficulty in establishing experimentally that a Higgs boson has been created, is to discriminate signals coming from a Higgs boson decay and other reactions which produce the same type of particle patterns hitting the detectors. Unfortunately, background reactions are much more frequent than the expected Higgs signals. Their discrimination relies on complicated methods. First, one needs to combine theoretical predictions and independent experimental measurements in order to estimate precisely the number of background reactions. Second, one needs precise theoretical predictions for the number of Higgs signal events. The latter depends on the mass of the Higgs boson and other properties, such as its coupling to other elementary particles.

6. Searching for a Higgs boson at accelerator experiments

In contrast to the mechanics of large objects which is deterministic, collisions of elementary particles with identicaly prepared initial conditions yield products which are, in general, different. In a microscopic experiment, all outcomes are possible as long as they are consistent with conservation of energy, momentum, the electromagnetic charge and other charges. Quantum laws prevent us from knowing which of the many possible outcomes will happen in a given collision. It is therefore impossible to prepare at an accelerator experiment a single collision which will produce a Higgs boson signal. Nevertheless, quantum laws determine fully the probability of an outcome to materialize. If we make a large number of particle collisions at a collider such as the Tevatron and the LHC, we can determine from first principles the fraction of them which yield a Higgs signal event.

The search for a Higgs boson is statistical. It is based on measuring the ratio of the number of candidate Higgs boson signal events and the total number of reactions. This is then compared to the probability that candidate signal events originate from background processes and the probability that they originate from both background processes and a true Higgs boson decay.

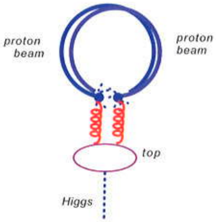

Figure 1: The simplest Feynman diagram for the production of a Higgs boson at the LHC

7. The probability of a Higgs boson signal

How can we compute the probability for a Higgs boson signal or a background reaction ? Given a quantum field theory, such as the Standard Model, we have precise rules to write a mathematical expression for the probability of a physical process to take place. This is the square of the magnitude of a complex number, the probability amplitude,

$$\text{Probability} = |\text{Amplitude}|^2.$$

The probability amplitude has an intuitive pictorial representation. It is the sum of all possible diagrams which we can draw, transforming the set of particles before a collision takes place to the set of particles observed after the collision.

$$\text{Amplitude} = \sum \text{Feynman Diagrams}$$

The rules of transforming a set of particles in the initial state to another set of particles to the final state are simple.

- Particle interactions occur at single space-time points, where "old" particles can be destroyed and "new" can be created. In a Feynman diagram, these are denoted with vertices, points where "particle lines" meet.
- In between interaction points, particles propagate freely. In a Feynman diagram, the free propagation of a particle is denoted by a line. Different types of particles are drawn with a different line (wiggly, dashed, straight, different color, etc) to distinguish them.

A Feynman diagram is much more than a picture. Each interaction vertex and each particle line have their own probability amplitude to occur. These are mathematical expressions of the energy, the momentum and the various charges of the freely propagating particles or the particles in a vertex. A Feynman diagram is made up from these expressions, multiplying together all the probability amplitudes corresponding to its vertices and lines.

In Fig. 1 we draw the simplest Feynman diagram where protons from the accelerated beams at the LHC can be transformed into a Higgs boson. Gluons from the protons, the binding particles of the strong interaction, are denoted with the spiral red line. Top quarks, particles which are similar to the "up" quark in the proton but about 190 times heavier than the proton, are drawn with a violet solid line. A Higgs boson is drawn with a dashed line. The Standard Model predicts, among many others, the following interactions (vertices) :

- A gluon can split into a top quark particle and its anti-particle. Let us denote the mathematical expression for the probability amplitude of this interaction as $\mathcal{M}_{gt\bar{t}}$
- A top quark particle and its anti-particle can be fused into producing a Higgs boson. Let us denote the mathematical expression for the probability amplitude of this interaction as $\mathcal{M}_{t\bar{t}h}$

The Feynman diagram is, up to some factors, simply the product

$$\text{Simple Feynman Diagram } \sim \mathcal{M}_{gt\bar{t}}\mathcal{M}_{t\bar{t}}\mathcal{M}_{t\bar{t}h}\mathcal{M}_{t\bar{t}}\mathcal{M}_{gt\bar{t}}\mathcal{M}_{t\bar{t}},$$

where $\mathcal{M}_{t\bar{t}}$ is the probability amplitude for a top-quark to propagate in between two interaction points.

8. Approximation methods for probability amplitudes

We can think of an infinite number of more complicated Feynman diagrams which transform a pair of gluons from the proton (and anti-proton) beams of the Tevatron and the LHC accelerators to Higgs bosons. Two such diagrams are illustrated in Fig.2. Notice that they contain a larger number of vertices and particle lines. In comparison to Fig.1 we encounter a different Standard Model interaction vertex, where a gluon splits into two other gluons.

Figure 2 : More complicated Feynman diagrams which contribute to the production of a Higgs boson at the LHC, transforming gluons from the protons to Higgs bosons.

All Feynman diagrams, every imaginable sequence of vertices and propagating particles which transform gluons of the initial state to a final state with a Higgs boson, contribute to the probability amplitude for observing a Higgs signal. This is a truly amazing feature of quantum laws, in contrast to the laws of classical mechanics where all intermediate steps in the evolution of a system can be determined fully. In quantum physics, it appears that everything which may happen in between observations (initial and final states) does happen, in the sense that the corresponding Feynman diagram contributes to the real probability for the outcome of the final observation.

The number of Feynman diagrams for any physical process is infinite.

However, our mathematics suffice to compute only the simplest ones. Feynman diagrams need to be evaluated for all possible values of energies and momenta of the particles propagating in between vertices. These give rise to multiple integrations which are very hard or, in most cases, impossible to perfom. An additional complication arises from the fact that an indivindual Feynman diagram is not always well defined mathematically for the parameters of our physical world, i.e. in four space-time dimensions and for elementary particles with real (non-complex) energy. Rather, it is the sum of groups of them which is well defined for physical parameters. A mathematically complicated procedure of using results of indivindual Feynman diagrams obtained with non-physical conditions is always necessary, in order to construct their physical sum.

It turns out that Feynman diagrams which are the easiest to draw, make up the most important contributions to the probability amplitudes of physical processes. Probability amplitudes for interaction vertices, such as the ones for the splitting of a gluon into two quarks $\mathcal{M}_{gt\bar{t}}$ or two gluons $\mathcal{M}_{ggg}$, are small at high energies, and proportional to an energy dependent "coupling constant",

$$\mathcal{M}_{ggg} \sim \mathcal{M}_{gt\bar{t}} \sim g,$$

which is characteristic of the strength of the gluon and quark interaction. A Feynman diagram which has more interaction vertices is therefore smaller than Feynman diagrams with less vertices. For example, the left diagram of Fig.2 is suppressed by a factor $\mathcal{M}_{ggg}^2 \sim g^2$ and the right diagram of the same diagram by a factor of $\mathcal{M}_{ggg}^4 \sim g^4$ in comparison to the simplest diagram for Higgs production of Fig. 1.

We can approximate the probability amplitude of a physical process by ordering the Feynman diagrams according to their power of the coupling constant g, starting from the smallest powers. We can impove our approximation, by computing Feynman diagrams of higher and higher orders in g, as long as we are able to develop mathematical methods for the increasingly difficult multiple integrations.

9. Precision predictions for Higgs boson signals at the Tevatron and the LHC

The leading order approximation, including only Feynman diagrams of order g^2, for the probability of a Higgs signal was derived already in the 70's. Such an approximation is a very rough order of magnitude estimate. It is insufficient for the detailed comparisons which are perfomed against experimental data at the Tevatron and the LHC.

The next improved approximation included also Feynman diagrams of order g^4. It was only made possible in the 90's after important technical breakthroughs methods and courageous individual efforts by a few theoretical physicists. The correction from the new Feynman diagrams to the number of Higgs boson signal events turned out to be very large, reaching the magnitude of the leading order approximation. This was a serious problem, since one could not trust that the remaining uncalculated Feynman diagrams were really suppressed. The approach of obtaining a good approximation for the probability of Higgs boson signals seemed unreliable. For a long time, it was an outstanding problem to compute the corrections from even more difficult Feynman diagrams at order g^6.

We have developed new methods which allowed such computations for the first time. We found that Feynman diagrams of order g^6 are contributing much less than the previous orders. Due to these computations, we are now able to simulate Higgs boson signals at the Tevatron and the LHC, in their finest kinematic details, with a theoretical precision of about 10%. Such an excellent precision has allowed the Tevatron to become sensitive to potenital Higgs boson signals, besides the rather limited statistical power and small energy of the collisions.

A discovery of a Higgs boson as predicted by the Standard Model should be possible at the most powerful accelerator, the LHC. When this happens, our simulations of the signals should be in agreement with the experimental results, unless the Standard Model is not correct. The high precision of our simulations is indispensable in order to answer this very important question on the validity of the Standard Model. We are now extending our simulation of Higgs boson signals to include more complicated models beyond the Standard Model, with new symmetries and additional forces. Proposals for such models are well motivated. The rate of producing Higgs bosons at the LHC, will be a very important test for these candidate physical laws at very high energies. The next few years will be a very exciting period for particle physics. After long efforts, we have achieved a great degree of confidence in our simulation of the most elusive elementary particle in history, the Higgs boson. We hope that its discovery will allow us to open finally understand how mass is generated for elementary particles, a question pending for almost the last half century. This question, may be connected with other cosmological puzzles, such as why we do only see a fraction of the total mass in the universe. We hope that the discovery of the Higgs boson will allow us to unlock many of the secrets of the physical laws at high energies.