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Vacuum, Colliders, and Origin of Mass

Vacuum in particle physics

The notion of vacuum and its structure plays a fundamental role in particle physics, one which is not just conceptual but has profound and observable consequences. As we discuss below, the properties of the vacuum are directly related to the presence of symmetries in particle interactions and, in particular, to the concept of the origin of mass. It turns out that the masses of fundamental particles are not arbitrary static quantities, but instead come from a dynamical mechanism, one which we are starting to probe now, with the discovery of the Higgs boson.

In order to understand the nature of vacuum and how we define it in particle physics, let us review some basic principles of the underlying theory used to describe nature at shortest known distances. Current theoretical basis for understanding properties of elementary particles and their interactions is quantum field theory (QFT). This ontological framework was developed from quantum mechanics of the 1920's to incorporate relativity and describe multi-particle systems. It serves as the basic tool for modern understanding of all particle interactions (apart from gravity).

The necessity of using fields as basic constituents to describe particles came from Dirac's (Dirac, 1932: 60) prediction of anti-particles. His famous equation (Dirac, 1928: 610) predicted that for every observed particle with half-integer spin (called a fermion), such as electron, there exists a corresponding anti-particle with the same mass but opposite charge. Thus, anti-matter was predicted and in and the following year Anderson (Anderson, 1933: 491) discovered the anti-particle of electron, the positron, and thereby vindicated Dirac's theory.

The existence of anti-particles posed a challenge to quantum mechanics. By design, the standard theory described systems with a fixed number of particles.

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On the other hand, if enough energy were available, a particle-anti-particle pair could be created, thus changing the number of particles in the system. The way QFT deals with this problem is that it assigns a field to each type of particle and then describes an individual particle as an excitation of this particular field from the ground state. For example, an electron field is postulated and, by applying a local excitation, a real electron is created.

The nature of vacuum in QFT

Once we embrace the QFT framework, an immediate consequence is a profound change of how we think about the vacuum. Classically, one would define vacuum as the absence of matter, a state without particles. In QFT, fields pervade entire space-time and one cannot do away with matter. Even if there is not enough available energy to create a real particle-anti-particle pair, such pairs can exist virtually for a very short period of time. Thus space is not completely empty of matter, at least not in the quantum sense. Therefore, an operational definition of vacuum is used. It is defined not as the absence of matter but as the state with the lowest possible energy, a ground state upon which excitations are created, interpreted as particles.

Such a definition of vacuum has interesting consequences. Vacuum can have physical properties which differ from one type of field to another. One such property is the value of the field in the ground state. Since QFT is designed to be a relativistic framework, relativity imposes constraints on the value of the field in the vacuum. In particular, the field in the ground state should not point in any particular “direction” that would break relativistic invariance. Therefore, the only field that can have a non-zero value of the field (so called vacuum expectation value) is one without an intrinsic direction. This obviously excludes particles with non-zero spin, such as fermions with spin 1/2 and vector bosons with spin 1. It leaves us with a unique option and the only field without an intrinsic compass, i.e. a scalar field with spin zero.

Symmetries and their breaking

The modern way to describe interactions between particles is to impose a special kind of symmetry on the equations of motion. In order for the equations to be symmetric, a set of interaction fields has to be introduced. These symmetries depend on space-time coordinates and are historically called gauge symmetries while the corresponding interaction fields are termed gauge bosons.

Gauge symmetry is explicit in the Dirac equation when electrons interact by an exchange of photons. This interaction remains the same when a gauge transformation is performed. This modern description of the electromagnetic interaction within QFT, developed by Tomonaga (Tomonaga, 1946: 27), Schwinger (Schwinger, 1948:1439), and Feynman (Feynman, 1948:769), is called quantum electrodynamics. The key step of development turned out to be gauge symmetry. Experimentally, this interaction has a very long range, which requires the photon to have a very small mass, experimentally indistinguishable from zero.

The success of the Standard model (SM) of elementary particles is that the other two known interactions, the strong interaction responsible for nuclear forces and the weak interaction responsible for nuclear decays, can also be described using the same formalism of gauge symmetry. For each force there is a symmetry and a corresponding gauge boson. The gauge bosons of the strong interaction are called gluons, because they “glue” the constituents in the nucleus, while the weak interaction bosons have a less imaginative name, the W and Z. In contrast to the electromagnetic interaction, the weak force has a very short range, which requires the corresponding gauge bosons to have a large mass.

The development of the theory of weak interactions starts with Fermi’s (Fermi, 1934: 161) attempt to formulate a theory, following the footsteps of Dirac. He imagined a point-like interaction to describe beta decay, the emission of an electron from a nucleus. This theory was known to behave very badly at high energies but it paved the way for a successful low energy description. The challenge was to find a well-defined theory of weak interactions at all energies.

Gauge theory of electro-weak interactions with massive gauge bosons was introduced by Glashow (Glashow, 1961: 579), extending the basic idea of his advisor Schwinger (Schwinger, 1957: 407). Glashow introduced the mass of the gauge boson by hand and thereby directly broke the gauge symmetry, hoping a way around this obstacle can be found. It was known that theories with massive gauge bosons lead to inconsistencies when quantum corrections are considered. Glashow was well aware of this problem, but chose to ignore it and constructed a physically viable model, which was not taken very seriously at the time. His intuition was good and the problem of massive gauge bosons was solved in an unexpected fashion, by way of spontaneous symmetry breaking (SSB).

All the experiments so far confirm the existence of underlying gauge symmetries of particle interactions. But what about the vacuum? It is well known that the ground state may not necessarily have the same symmetric properties as equations of motion themselves. That is, a solution from symmetric equations with the least energy may not be symmetric. When such a situation occurs, one says that the symmetry is hidden or broken spontaneously. There are familiar examples of such breaking in many physical systems. An example of spontaneous symmetry breaking in a social context was given by Abdus Salam, one of the fathers of the SM. Imagine a dinner at the round table with symmetrically placed wine glasses. This situation is completely left-right symmetric and it is only when the most important (or thirsty) person decides on which glass to take and the others follow that the initial symmetry is broken.

The Higgs mechanism

The mechanism of SSB has been widely used in particle physics. Particularly important for the understanding of SSB were the contributions of Nambu (Nambu, 1960: 648) and Goldstone (Goldstone, 1961: 154). They showed that when a global symmetry is broken, a physical massless particle should exist. This Nambu-Goldstone theorem was very helpful in developing the theory of strong interactions, but it posed a problem for a consistent description of weak interactions. Experiments indicated that weak gauge bosons should be massive, which in principle could be described through spontaneous symmetry breaking but, since no massless particles corresponding to such breaking were observed, there seemed to be a paradox preventing the use of SSB to describe the weak interaction.

The solution to the paradox was the work of Anderson (Anderson, 1963: 439) Brout and Englert (Brout, 1964: 321), Higgs (Higgs, 1964: 508), and Guralnik, Hagen and Kibble (Guralnik, 1964: 585), now known as the Higgs mechanism. Anderson was the first to realise that when SSB was applied to a gauge symmetry the massless Goldstone boson disappeared. A relativistic particle physics model was constructed by Higgs, who showed this is indeed the case. If the potential of the bosonic field is such that the ground state is not symmetric, the scalar field will get a non-zero value in the ground state. As a result, the gauge bosons acquire a mass, and the previously massless Nambu-Goldstone boson are now incorporated as an additional degree of freedom for the massive gauge boson (massless particles only have two degrees of freedom, or polarisations).

This result was of great importance. It opened the doors for a consistent description of massive gauge bosons and, more importantly, predicted the existence of a massive elementary scalar, the Higgs boson. Glashow's theory of weak interactions with massive gauge bosons could now be made consistent by employing the Higgs mechanism. This was precisely the work of Weinberg (Weinberg, 1967: 1264) and Salam (Salam, 1968: 367), who constructed a mathematically consistent theory of weak interactions that correctly described all the weak processes with heavy gauge bosons. It is only after their result that the interactions of the Higgs boson were predicted and one could start looking for it.

Origin of mass

After three years of running the Large Hadron Collider (LHC), two experiments, ATLAS (Aad, 2012: 716) and CMS (Chatrchyan, 2012: 716), both confirmed the existence of the Higgs boson nearly 50 years after its prediction, confirming the idea of SSB. It seems we really live in a universe described by symmetric equations and an asymmetric vacuum. Now that we are able to produce the Higgs boson, the particle excitation above this non-trivial ground state, we can start probing the physical properties of the vacuum and, in particular, the origin of particle masses.

Dynamical mass origin

The concept of mass we usually subscribe to is one of inertial or gravitational mass of everyday objects. The former describes the resistance of a moving object to an external impulse, and the latter refers to the response to the presence of other massive objects. Classically, we consider mass as a given static parameter, which can be measured but typically does not require an associated mechanism for its emergence.

With particles[1], the situation seems to be quite different. The Higgs mechanism transcends the static role of the mass as a given arbitrary parameter and provides a dynamical explanation of its origin. By this we mean that the size of particle mass, which we can measure as a response to an external field, is now related to a completely different process, which is the decay of the Higgs boson.

When we describe the interactions of any given particle with the Higgs field and the Higgs obtains a vacuum expectation value, this given particle will not only couple to the Higgs particle excitation, but also to the Higgs ground state, the vacuum expectation value v. This vacuum expectation value is the only explicit energy scale in the SM and sets the overall mass scale for all other particles. Any particle that receives its mass from the Higgs mechanism, will end up with its mass proportional to v, up to a constant where c differs from one particle to another.

This mechanism for providing the mass was used by Weinberg (Weinberg, 1967: 1264) to describe massive gauge bosons of Glashow (Glashow, 1961: 579), the W and Z. An attractive feature here is that the proportionality constant c is just the weak interaction gauge coupling. Moreover, the ratio between the W and Z mass is completely fixed by low energy experiments and was confirmed when W and Z were observed at the SPS collider in the early eighties.

A beautiful property of the SM is its minimality. Weinberg realised that, with a single Higgs field, one simultaneously provides a mass for the gauge bosons and also all the charged fermions. This can be done by coupling fermions directly to the Higgs field via the so-called Yukawa interaction[2]. To each charged fermion corresponds a unique Yukawa coupling and the latter's size determines the mass of the particle. The stronger it couples to the Higgs vacuum, the more massive the fermion is. At the same time, the bigger the coupling to a given fermion is, more often the Higgs boson decays into it and this is how the dynamical origin of fermion mass can be tested.

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[1] Here we discuss the masses of elementary particles, such as electrons, and not composite objects, e.g., protons and neutrons, that are made out of elementary particles, quarks.

[2] Hideki Yukawa was the first to use the fermion-fermion-boson coupling in his theory of strong interaction, where the effective interaction between protons and neutrons is mediated by light bosons, called pions (Yukawa, 1935: 48).

Finally, even the mass of the Higgs boson itself is proportional to the vacuum expectation value. The proportionality constant here is the Higgs self-coupling, with four interacting bosons. Remarkably enough, it may well be that almost all the particles we know might share the same origin of mass, which follows from the non-trivial vacuum of the Higgs field.

Probing the vacuum

The method of physically probing the vacuum structure and the origin of mass is deceivingly simple. First, one should produce the Higgs boson, then observe its decays, and finally compare the decay channels to the predictions of the SM. In order to produce the Higgs boson, as for any heavy particle, one should have enough energy to excite it from the ground state. For this one needs a colliding machine with sufficient available energy. The problem with the Higgs boson is that its mass could not be predicted. This is in contrast to the W and Z gauge bosons, whose mass was bounded prior to discovery to a fairly narrow range by low energy data and other measurements, such as neutrino scattering via neutral currents (Hasert, 1973: 121). The predicted range was up to about 170 times the mass of the proton (m_p), and the SPS collider discovered both W and Z with masses around 90 m_p. As for the Higgs mass, the preferred value coming from a combination of many different experiments was around 110 m_p, but a precise upper bound was not known and it could have been as heavy as 800 m_p.

SPS collider that discovered the W and Z was not powerful enough to produce the Higgs and a new machine was needed. First hope for discovery was a large electron-positron collider (LEP), which came short in energy by a fairly small amount, as we now know. Later on, a proton-anti-proton collider, the Tevatron, started operating in '87 at Fermilab. Its energy was almost five times larger than SPS's and it managed to discover the heaviest known fermion in the SM, the top quark. Alas, it still lacked the energy to observe the Higgs. Finally, the LHC started colliding proton-proton beams in 2009. On July 4th 2012, both detectors, CMS and ATLAS, announced the discovery of a new fundamental scalar, most likely to be the Higgs boson, with the mass at around 134 m_p (CMS, 2012: www). The discovery of the Higgs boson required an extraordinary experimental effort. After building the most powerful microscope that ever existed, the experimental groups were faced with a task of discovering a needle in a haystack. Even worse, the Higgs boson is produced in only one out of ten billion events, a large haystack indeed. Therefore, a lot of data needs to be collected. The detectors record and analyse several petabytes of data per second, but keep only the most interesting events and store them off-line for further study. With the amount of data collected after roughly three years of running, the LHC has produced around 10.000 Higgs bosons. Not all of these events can be used for analysis, since they may resemble the background too much, but they still provide us with enough statistics to make statistically sensible statements about the Higgs and its vacuum structure.

A particularly clean channel, now seen with great statistical confidence (6.7 σ) at the LHC (CMS, 2012: www), is the decay of the Higgs boson to a pair of Z bosons, shown on the left side of Fig. 1. This process happens at first order in perturbation theory with a fairly high rate; Higgs decays in this way around 3% of the time. It gives a very distinct signal when the two Zs decay and both detectors, CMS and ATLAS, measured it pretty well. Results agree with the SM expectations therefore the dynamical origin of the Z mass via the Higgs mechanism is now becoming apparent for the first time.

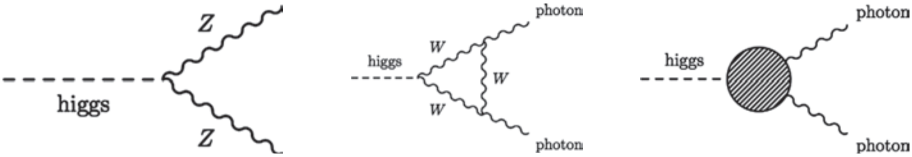

Figure 1: Decay channels of the Higgs boson. Left: tree level decay to a pair of Z bosons. Centre: a loop mediated decay to two photons through virtual W bosons. Right: additional possible contribution to the di-photon channel due to unspecified new physics.

Another channel which is conceptually important is the decay of the Higgs boson to a pair of photons, seen in the centre and right of Fig. 1. What makes this mode interesting is the fact that it does not happen in the first order of perturbation, but instead only proceeds through virtual contributions, i.e. it probes all the vacuum fluctuation that couple to the Higgs. One such contribution comes from the SM with the exchange of virtual W bosons, shown in the centre of Fig. 1.

The di-photon decay mode of the Higgs boson is now clearly seen and provides us with a direct probe of the vacuum structure. Any charged particle that couples to the Higgs boson will affect this process via quantum fluctuations as illustrated in Fig. 1 right, even if we have not yet observed it directly. Processes of this type, suppressed at first order and therefore sensitive to heavy particles, are particularly welcome since they can provide hints on what to expect in the future. At the moment, the SM prediction seems to agree well with the experiment.

Origin of fermion masses

The visible matter in the universe is composed of fermions, such as protons, neutrons, and electrons. The electron seems to be an elementary particle, while protons and neutrons are made out of constituent fermions, named quarks. Proton and neutron are made out of two types of quarks, called "up" and "down" quarks. Together with the electron neutrino, these four particles form the first generation (family) of fermions. However, this is not the entire story. We now know that there are two more generations of particles present in nature, exact copies of the first, except for their larger mass.

What is the origin of fermion mass? We are just starting to unravel the answer to this question, with the discovery of the Higgs boson. As we will see, the complete answer is still far from obvious. Although the general outline is becoming clear, it may take a long time, and a lot of theoretical and experimental effort, to get a clear picture of what is going on.

The relativistic equation for fermions was discovered by Dirac together with its prediction of antiparticles. The equation works beautifully for electromagnetism, even when the fermion masses are put in by hand. This is because the fermion mass respects the symmetry of electromagnetic interactions and allows for a self-consistent quantum theory. But, with new experiments, it became clear that the nature of weak interaction is such that a mass term for fermions will break the underlying symmetry of weak interactions. Like with gauge boson mass in Glashow's model, this is problematic when quantum corrections are considered.

The way out of this fermion mass problem was very elegant and was the culmination of works of Yukawa and Higgs et al., written down by Weinberg (Weinberg, 1967: 1264). As discussed above, Yukawa used a direct coupling of fermions to scalar bosons to describe strong interactions. The brilliance of Weinberg's work was to use this coupling for the electron with a different scalar, the Higgs boson. As the Higgs boson has a non-trivial vacuum after SSB, fermions couple directly to its vacuum expectation value and, therefore, acquire a mass. It is theoretically very pleasing to have such a minimal model with a single field providing mass to all other particles.

The masses of fermions depend on the size of the coupling constant, the so-called Yukawa coupling. The bigger the mass, the bigger the coupling, and the more likely the Higgs boson is to decay into such a particle-anti-particle pair, as long as it is lighter than the Higgs mass. Therefore, the decays to heavier generations are easier to observe at the LHC. Both CMS and ATLAS are starting to gather enough data to obtain a statistically meaningful signal (CMS, 2012: www). The second and first generation fermions are significantly lighter, therefore, the rate at which they would appear in the Higgs final state is much smaller, and also the signal is more difficult to distinguish from the background. LHC may not be the right machine to resolve the origin of charged fermion mass for the lighter two generation, but perhaps the next generation collider will provide the ultimate answer to this issue.

Nevertheless, the LHC has provided an ultimate answer to one long standing question, that of the number of generations. By this we mean a strict carbon copy of existing families, which obtain their mass solely from the Higgs mechanism. As mentioned above, even if we cannot see the fourth generation directly, it would affect certain processes, in particular the decay to two photons. Since the observed rate is in good agreement with the three generations of SM fermions, an extra family is ruled out with high confidence.

Origin of neutrino mass

The discovery of the Higgs boson and its properties measured so far confirm predictions of the SM. But there is one clear prediction which turned out to be incorrect and that is the mass of neutrinos. At the time the SM was constructed, there was a prevailing belief due to absence of proof on the contrary, that neutrinos were massless. Following this line of thought, the model of leptons as written by Weinberg had such a structure that neutrino mass could not exist.

Gradually, the question of neutrino mass started to become acute in the following way. With the techniques developed by Ray Davis (see Cleveland, 1998: 505 for a review), it was possible to observe neutrinos and measure their flux. At the same time, it was known that the Sun should be producing a large amount of neutrinos in its burning cycle, due to the work of Bahcall and others. When measurements were compared to theoretical predictions, the numbers did not match, even when various uncertainties were taken into account, resulting in the solar neutrino puzzle.

An altogether different solution to the solar neutrino puzzle was put forward by Bruno Pontecorvo, an Italian physicist who was the godfather of most discoveries behind neutrino physics. He suggested (Pontecorvo, 1957: 549) that if neutrino had mass, then the neutrino produced in the Sun need not be the same as the one that arrives to the Earth. Instead, it would oscillate to a different kind, which could not be detected by the experiment. Although this was a very simple explanation, it was largely ignored due to the clear prediction of the SM (and other theoretical ideas developed at the time, such as some grand unified theories).

This issue persisted and intensified over the years, though many dismissed it due to the complicated solar model and experimental difficulties in measuring the neutrino flux. The final verdict came in late nineties from the Super-K experiment in the Kamioka mine. Although the initial aim of Super-K was to look for proton decay, it ended up measuring many neutrino events (Fukuda, 1998: 81). These neutrinos could not have been produced in the Sun, but came instead from the Earth's atmosphere. When cosmic rays hit upon the Earth, they produce a massive shower of particles, which in turn decay to neutrinos. This process is much better understood than the solar model and the results of Super-K could not have been explained by other means than neutrino oscillations. Once the oscillation explanation is accepted, all the results become consistent and the proof for massive neutrinos is now firmly established.

The existence of neutrino mass poses an obvious question. What is the theory of neutrino mass? Surely it is not the SM, as it predicted neutrinos to be massless. And what is the origin of neutrino mass, i.e. is it related to the origin of other charged particles, the Higgs mechanism? These issues remain unsolved to this day, although there are theoretical ideas about how to go beyond the SM and uncover the theory behind neutrino mass. To understand the enigma of neutrino mass, let us go back to the ground-breaking work that still forms a theoretical basis in the field of neutrino mass.

Dirac or Majorana

The work of Ettore Majorana was a hallmark paper (Majorana, 1937: 171) that made a profound impact on neutrino physics. Shortly before his mysterious disappearance, Majorana wrote a paper on the possibility of describing fermions with only half the degrees of freedom that were usually employed.

In the SM, all the charged fermions obtain their mass by coupling to the Higgs field through the so-called Dirac mass. For this mass term to exist, fermions need to be described by a complete Dirac spinor, containing twice the degree of freedom a Majorana spinor can have. Historically, these are called left- and right-handed spinors. For a charged fermion, this is the only possible mass term that one can imagine without breaking the symmetry of the weak interaction. If both components need to be present, then there is a prediction that for every particle there exist a corresponding anti-particle. Majorana's contribution was to show that there exist a consistent way of describing truly neutral massive fermions with only a single component of the Dirac spinor.

His idea immediately found a place in neutrino physics. Neutrinos do not carry electric charge so it seems natural to describe them with a Majorana spinor. The basic point is that if we use the Majorana spinor, it turns out the mass term will break any symmetry associated with the neutrino, i.e. Majorana neutrino is a truly neutral particle. This is in direct contrast to the work of Dirac, who predicted the existence of anti-particles. His prediction holds true: for any existing charged particle there is a corresponding anti-particle. But if a neutrino were Majorana, it would be truly neutral and therefore equal to its anti-particle. So which is it for the neutrino, Dirac or Majorana?

The formalism developed by Majorana is not innocuous; it has an immediate physical consequence that can distinguish a Dirac fermion from a Majorana. The physical impact was realised by Racah and Furry (Racah, 1937: 322) shortly after the work of Majorana. They suggested a particular type of nuclear decay in which the Majorana nature of the neutrino could be tested experimentally. The majority of nuclei decay through an emission of a neutrino and an electron, the so-called beta decay. There are rare occasions when this process is forbidden and the nucleus has to “jump” an atomic number to decay with a simultaneous emission of two electrons and two neutrinos at the same time. Maria Goeppert-Meyer was the first to realise that such double beta decay can take place at a very low rate – at the moment it is the slowest physical process we have ever measured. Following the work of Majorana, Racah and Furry realised that if neutrinos were truly neutral and massive, the double beta decay could occur even without the emission of neutrinos: a neutrino-less double beta decay.

One of the reasons why the Majorana nature of neutrinos and the search for neutrino-less double beta decay are important for physicists has to do with a certain type of symmetry. When a given process is very rare, physicists tend to assign a conservation rule, a symmetry. For example, in all the processes we observe, electric charge is conserved. Therefore, we are tempted to assign a charge number to all particles, and an opposite one to anti-particles, which is then conserved. The corresponding symmetry for electric charge is precisely the gauge symmetry of the electromagnetic interaction.

Suppose that instead of electric charge we assign a common charge to the electron and the neutrino, called the lepton number. Since all the experiments performed so far seem to conserve this number, lepton number conservation is a reasonable symmetry. But once we allow for a Majorana neutrino, its mass term will break it. This is because a Majorana neutrino, being made of a single spinor component, is a truly neutral particle, indistinguishable from its own anti-particle.

In the SM without neutrino mass, lepton number is conserved. With the unambiguous proof of neutrino oscillations from Super-K, it is clear that neutrino mass should be added once we go beyond the SM. In such a case, the lepton number could be broken and we should look for ways to test how good this symmetry really is (in any case testing fundamental symmetries is important in its own right). Neutrino-less double beta is an experiment designed to do this. It looks for a process in which one nucleus transforms to another without emitting neutrinos, only electrons. Therefore, the lepton number has increased by two units and the process clearly breaks the lepton number symmetry.

The search for neutrino-less double beta decay started almost immediately after the theoretical suggestion and has been going on ever since. Especially after the discovery of neutrino mass by Super-K, the search has intensified and there are currently around six experiments looking for this process, with more under way. This line of research is complementary to collider searches. It does not require high energy machines, but instead demands a lot of patience and dedication to eliminate the unwanted background and search for the signal. It is remarkable that both colliders and low energy nuclear experiments can simultaneously probe the same type of physics from different ends of the energy spectrum.

Left-Right symmetry

The SM predicted neutrinos to be massless and the prevalent mood at the time of its creation was that this should indeed be the case. But after the discovery of neutrino oscillations, one of the central issues in particle physics became the quest for a theory of neutrino mass. Despite the success of the SM, people nevertheless thought about theories which focused on other aspects of particle physics but necessarily ended up with massive neutrinos. Such theories, where a complete framework is constructed in order to follow a certain physics idea, may be our best bet for the theory of neutrino mass.

From theoretical considerations related to left-right symmetry and grand unification came a beautiful idea of the see-saw mechanism, which provides a modern understanding for the lightness of neutrino mass and naturally incorporates Majorana neutrinos.

The original idea that led to the see-saw mechanism is the concept of parity restoration at high energies. In the mid-50's, two brilliant young physicists, Lee and Yang (Lee, 1956: 254), showed that weak interaction is very special and profoundly different from the electromagnetic and strong interactions. While the latter two behave the same way if we replace left with right (a symmetry called parity), weak interactions break parity in a maximal way. Their result came as a great surprise to the community. However, due the prevailing belief that parity should remain a fundamental symmetry of nature for all interactions, Lee and Yang added a short paragraph to their work. They offered a possible solution with mirror extra families, which would restore the parity symmetry and put all the interactions on the same footing. The solution suggested by Lee and Yang turned out to be another beautiful idea killed by the ugly facts of nature. As discussed above, even a simple fourth generation is ruled out, not to mention an entire mirror world envisaged by Lee and Yang.

Apart from mirror families, there exists another, perhaps even more intuitive way to restore parity, called left-right symmetry. Such a theory was first suggested in ’74 by Pati and Salam (Pati, 1974: 703) who added a second weak interaction that also violates parity maximally, but in the opposite way, so that parity is eventually restored. Initially, it was thought that parity cannot be broken spontaneously, but the work of Senjanović and Mohapatra (Senjanović, 1975: 1502) showed that by using an appropriate version of the Higgs mechanism in left-right symmetric theories, this can indeed happen. Thus, parity could be a perfectly valid symmetry at very high scales, but the vacuum is asymmetric so we would perceive it to be broken at lower energies.

Neutrino mass and the see-saw mechanism

The way left-right symmetry works for fermions is that it treats both components of the Dirac spinor, called left and right-handed components, on the same footing at high energies – it is parity symmetric. But at low energies, this symmetry gets broken and weak interactions couple more strongly to one component of the spinor than the other and this is the source of parity violation.

The initial attempt to have a consistent left-right symmetry resulted in problems with neutrino masses, which turned out to be too large. If only Dirac type of masses were used, neutrinos would become heavy and with their mass would end up above the experimental limit. The way out of the impasse was provided independently by Minkowski (Minkowski, 1977: 421) and Mohapatra and Senjanović (Mohapatra, 1980: 912). The crucial point was the realisation that neutrinos can also have a Majorana mass. If this is allowed for, a beautiful solution emerges. One component of the neutrino spinor (roughly speaking a Dirac spinor is made out of two Majorana spinors) becomes very heavy, but as a result the other one is necessarily light – hence the name the see-saw mechanism.

A similar conclusion was reached in the context of grand unified theories (Glashow, 1980: 59), where all the different interactions are described by a single grand unified gauge symmetry. In this case, not only is a form of parity restored at high energies, all of the known interactions also merge into a single one. A particularly attractive gauge group (mathematical term is *SO(10)*) is the one in which the entire generation of fermions is described by one large spinor and, as it turns out, this spinor automatically contains a heavy Majorana neutrino. Both parity restoration and grand unification started with a distinct theoretical concept but ended up predicting neutrino mass long before the experiment. They both arrive to the same appealing explanation for the lightness of neutrino mass via the see-saw mechanism and both contain Majorana neutrinos. But how do we test these ideas? An indirect proof would be the observation of neutrino-less double beta decay, but to really uncover the theory behind neutrino mass, we would like to "see" the heavy Majorana neutrino directly and this is where colliders are needed.

Neutrino mass and colliders

Weak interaction is mediated by an exchange of heavy weak gauge bosons W and Z and they couple only to one part of the Dirac spinor, historically called the left-handed component. At low energies, their effect is seen in nuclear processes like beta decay. But only when they were observed at the SPS collider, was the origin of weak interaction conclusively established.

In order to start probing the theory behind neutrino mass, one would like to observe the microscopic nature of neutrino mass directly in colliders. In left-right theories, another weak interaction is postulated with analogues of W and Z that are heavier (they better be, since we have not seen them yet), and couple only to the other component spinor, the right-handed one. If the energy scale of parity restoration were light enough, the LHC would be able to produce the right-handed gauge boson W_R. Once produced, it can decay into an electron and a heavy neutrino, as suggested by Keung and Senjanović (Keung, 1983: 1427). If the heavy neutrino is a Majorana particle, its decay will violate lepton number and it could decay into another electron and two quarks. So from the initial proton-proton beam at the LHC, we would end up with a final state of two leptons and two quarks. The initial lepton number was zero and at the end it is two, so lepton number would be broken by two units, just like in neutrino-less double beta decay. Observing this process would unambiguously establish the microscopic origin of neutrino mass.

The exact method of looking for heavy neutrinos depends on their mass. With early LHC data, the signal was re-interpreted (Nemevšek, 2011: 83) and dedicated searches for heavy neutrinos and W_R by both CMS (Chatrchyan, 2012: 261802) and ATLAS (Aad, 2012: 2056) collaborations were carried out. Should the signal be observed at the LHC, it would directly connect the lepton number breaking at colliders to many rare processes at low energies, including neutrino-less double beta decay (Mohapatra, 1980: 912 and Tello, 2011: 106).

To complete the picture and have an ultimate understanding of the see-saw mechanism, one should be able to unravel the see-saw mechanism. Only recently were we able to show that, in the minimal left-right model, this can be done (Nemevšek, 2013: 110). By measuring the heavy neutrino signal at the LHC (Keung, 1983: 1427), one would be able to determine in what way neutrinos (both heavy and light) couple to the Higgs vacuum. In this way, left-right symmetry becomes a complete theory of neutrino mass, just like the SM is for charged leptons. Once the masses are known, all the Dirac Yukawa couplings can be predicted and these predictions tested at the LHC or future colliders.

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