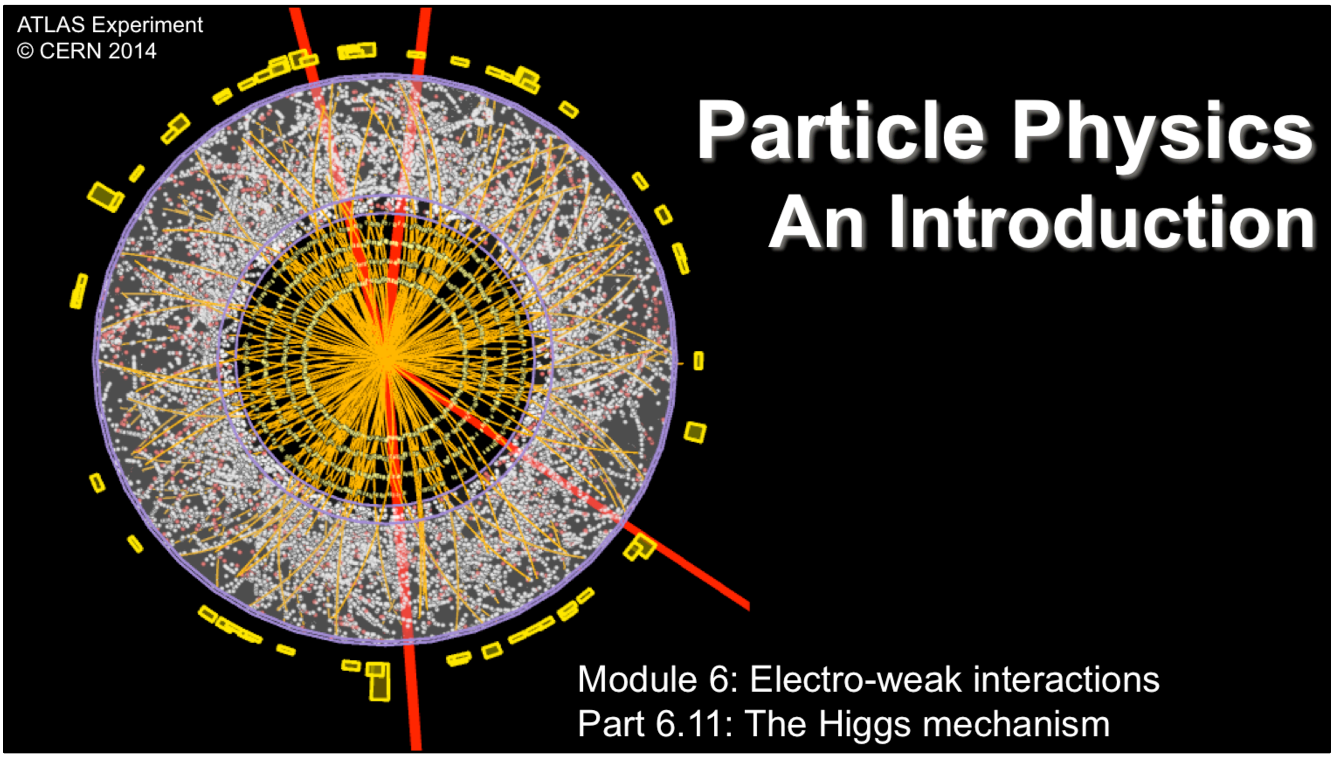
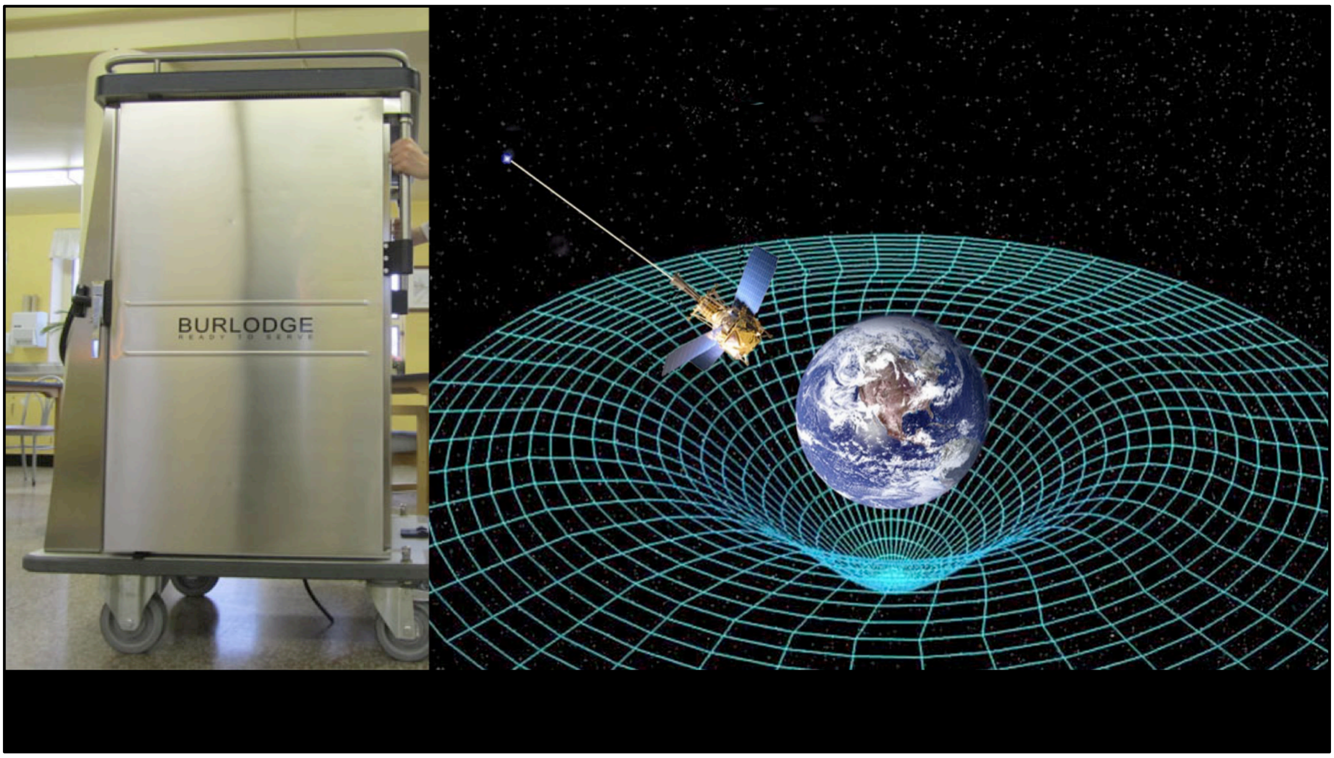


In this sixth module, we have discussed electro-weak interactions and now turn to the Higgs mechanism.

In this 11th video, we will introduce the dynamical generation of particle masses by this mechanism.

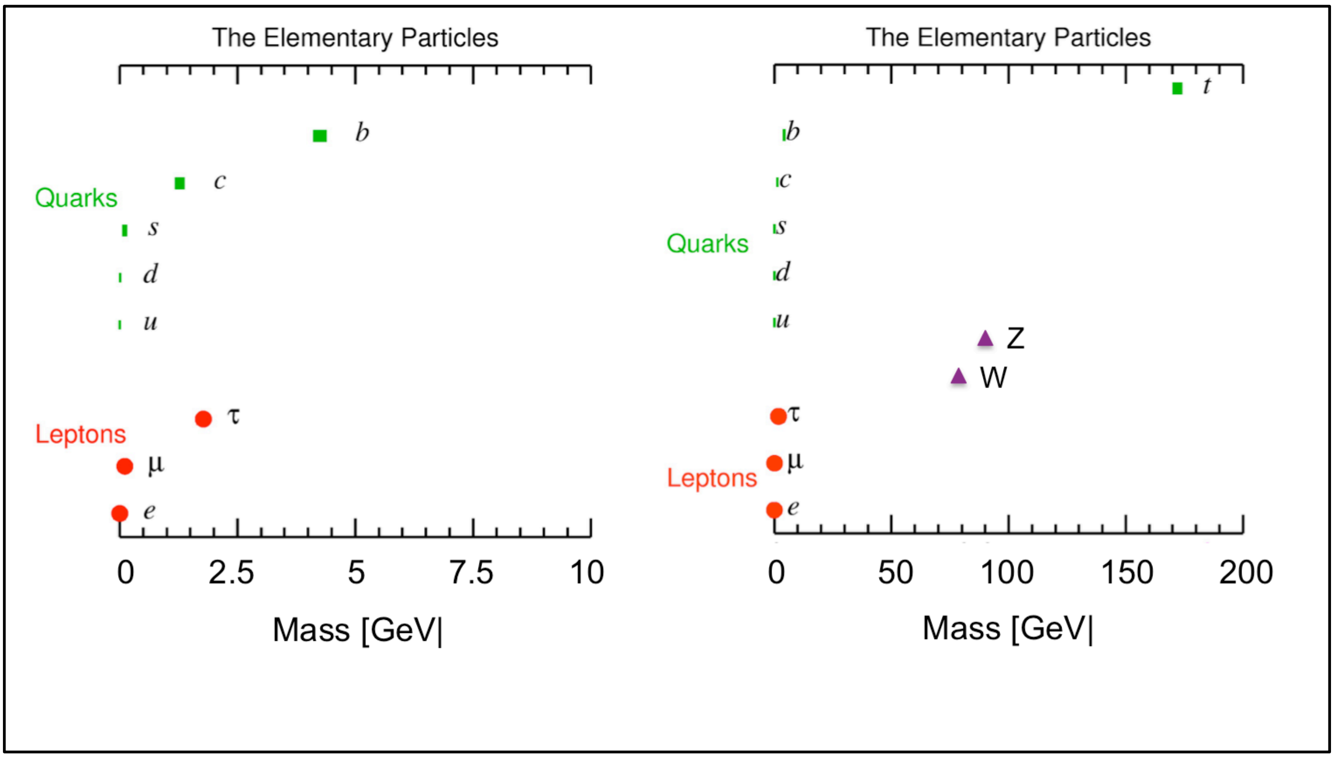
After following this video you will know:

- How to argue that mass cannot be an intrinsic property of particles;
- How what is called mass can be dynamically generated;
- How the Higgs mechanism realizes this, through the interaction of particles with the omnipresent Higgs field.
- And finally, you will know qualitatively how particles evolve in a vacuum filled with the Higgs field.

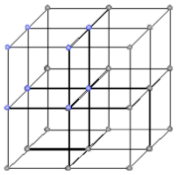


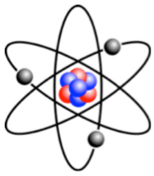
What is the **mass of an object**? There are two phenomena connected to mass:

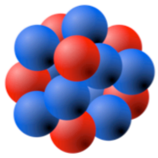
- First, mass is the property of an object, which "opposes" itself to acceleration according to Newton's law. This is called the **inertial mass.**
- At the same time it is the property of an object, which allows it to attract other bodies via gravity. This is the **gravitational mass.**
- It is the equality of these two properties which led Einstein to formulate **general relativity**, the only theory of gravitation known to date.

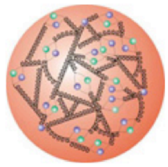


- But here it is only the **inertial mass** which is of interest here, the gravitational interaction is too weak to matter at the subatomic level.
- One measures the mass of a particle by observing the energy that it takes to create it at rest. Or by observing the invariant mass of its decay products. Or by observing its velocity at a given energy. It is in fact this last property of the mass that we must retain: **mass is the property that keeps particles from moving at the speed of light** no matter how energetic they are!
- The **particle spectrum** is extremely large, both as far as matter is concerned, with $m_\nu = O(\text{meV})$ up to $m_t \approx 170$ GeV, as well as for forces with $m_\gamma = m_g = 0$ up to $m_Z \approx 91$ GeV and $m_W \approx 80$ GeV.
- We believed, me and probably you too, that the mass of elementary particles – quarks, leptons and gauge bosons – was one of their **intrinsic properties**, like the electric charge, color, flavor, baryon or lepton number. But this is not true, mass is the product of a dynamic process, without which the mass of all the ingredients of the Universe would be zero.









$$M \simeq \sum M_{\text{atom}} \qquad 1\text{eV} < E_{\text{coh}}/A < 10\text{eV}$$

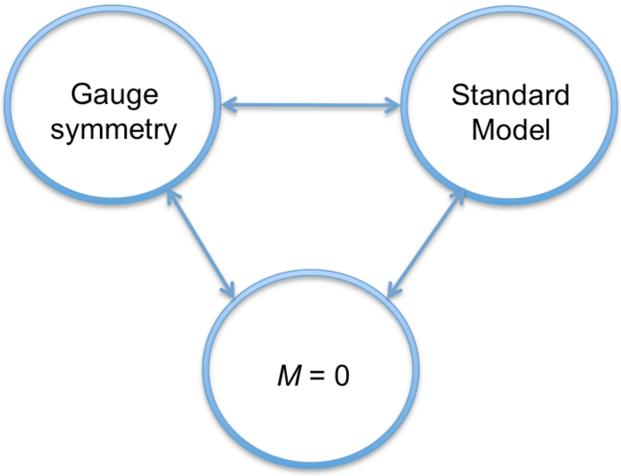
$$M \simeq \sum m_{\text{e}^-} + M_{\text{nucleus}} \qquad 5\text{eV} < E_I/\text{e}^- < 25\text{eV}$$

$$M \simeq \sum M_{\text{p}} + M_{\text{n}} \qquad E_B/N \simeq 8\text{MeV}$$

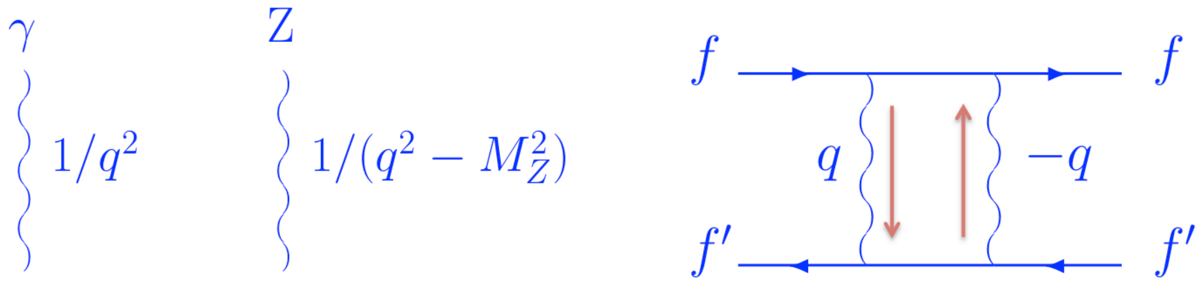
$$M_N \gg \sum m_{\text{q}} \qquad m_{\text{u}} \simeq m_{\text{d}} \simeq O(\text{MeV})$$

- Let us trace back the **origin of mass** across different objects scales.
- For **ordinary matter**, solids, liquids and gases, the mass is to a good approximation equal to the sum of the masses of their atoms. The cohesive energy in a crystal, for example, is between 1 and 10 eV per atom, small compared to the mass of the atoms.
- The mass of an **atom** is also pretty much equal to the sum of the masses of its electrons and its nucleus. The atomic binding energy is of the order of 5 to 25 eV per electron, small compared to the mass of the nucleus.
- This reasoning continues to be true at the nuclear level. The **nuclear mass** is not far below the sum of the masses of its nucleons, but with a more important binding energy, of the order of 8 MeV per nucleon, as we saw in the Module 2. But it is still small compared to the mass of nucleon, of the order of GeV.
- In summary, the mass of the matter in the Universe is **dominated by the mass of the protons, neutrons and electrons**, which populate it.
- But at the scale of the **nucleon** itself, this reasoning does not work anymore. Proton and neutron contain low mass quarks and massless gluons. The nucleon mass is dominated by their **binding energy**, it has a dynamic origin!
- But **quarks and electrons** do not have binding energy, because they have no substructure. So at least for them, could mass not be an intrinsic property?

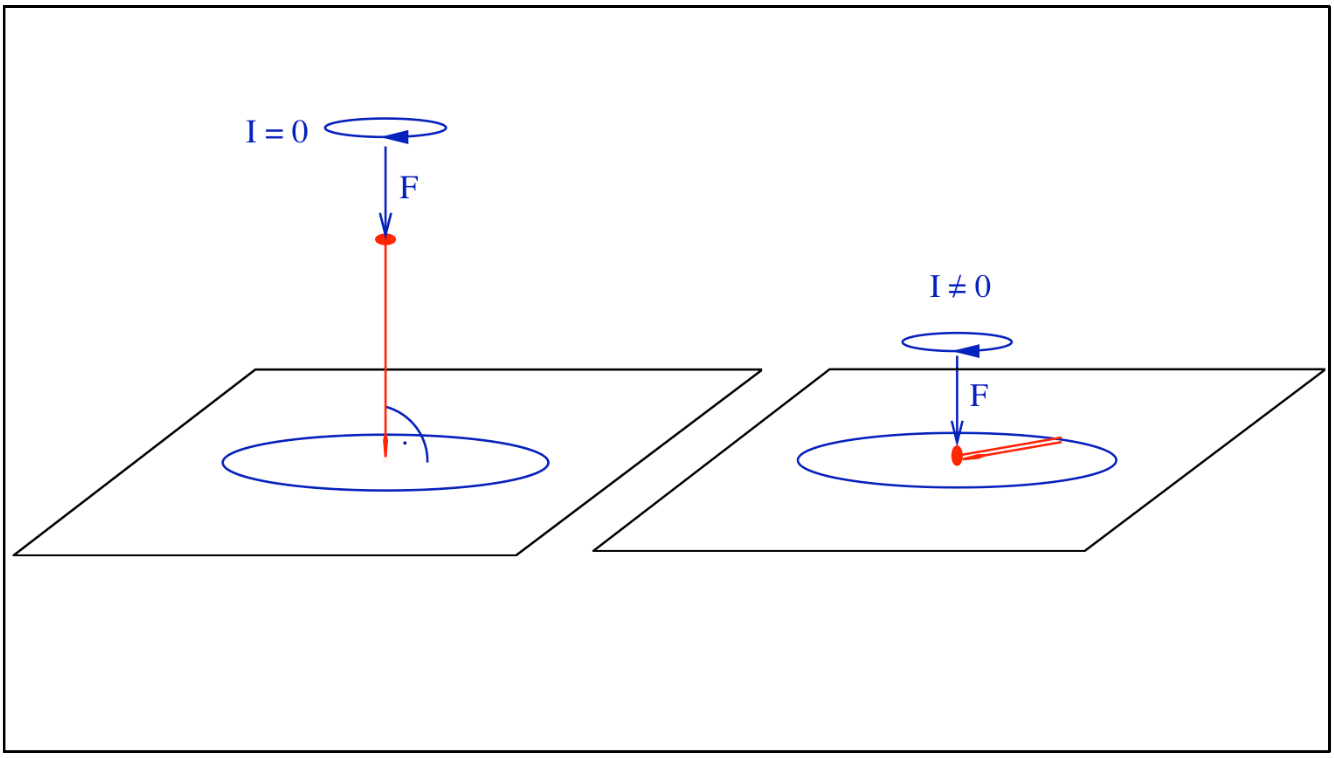
Amalie Emmy Noether (1882–1935)



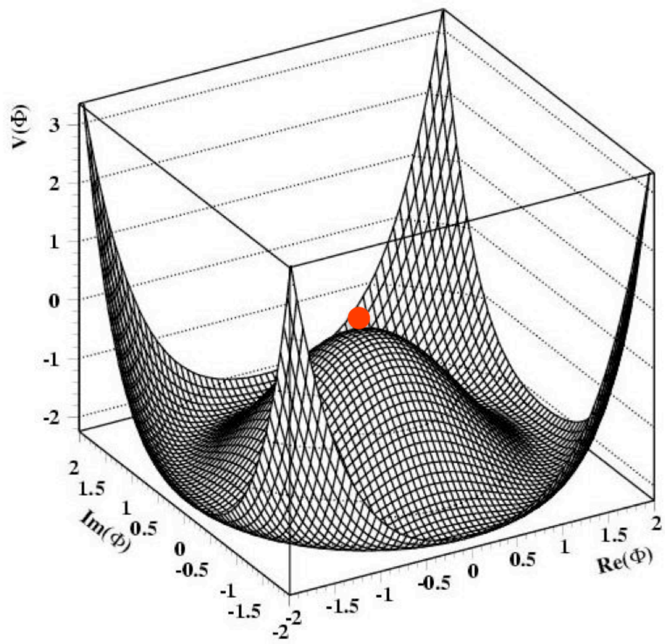
- The answer is **NO,** and the reason for this is quite subtle and fundamental at the same time.
- Continuous symmetries are closely linked to the conservation of physical quantities, by **Noether's theorem**.
- In particular **gauge symmetry**, the invariance of observables relative to a local phase change of the field, is the basis of the Standard Model of electro-weak and strong interactions.
- Gauge symmetry is in fact **necessary** to ensure the regularization of infinities in field theory, allowing to "absorb" them into measured quantities. Without this possibility, the Standard Model would not make any predictions. Yet its results agree with experiment everywhere so far.
- On the other hand, **an intrinsic particle mass**, for matter as well as for forces, **violates gauge symmetry.** For a massive field we do not have the freedom to change its gauge. In other words, the fact that all generations of matter in all families have a different and non-zero mass, and the fact that m_Z and $m_W \neq m_\gamma$ violate gauge symmetry.
- Consequently, mass must come from a **dynamic process** instead of being an intrinsic property, that particles are born with.



- Why can we not treat the **t quark as a very heavy u quark**, and the **Z boson as a heavy photon**?
- The problem comes from the **propagation** probability of heavy bosons. The probability amplitude for the exchange of a zero mass **photon** between two vertices is $1/q^2$, with q the four-momentum of the photon. This amplitude is thus inversely proportional to the invariant mass squared of the virtual photon, it has a pole at $q^2 = 0$, i.e. for a real photon. The amplitude gently tends to zero for $q^2 \rightarrow \infty$.
- For a **massive boson**, on the contrary, the propagator amplitude is $1/(q^2-M^2)$, it has a pole at $q^2 = M^2$. For ordinary reactions this does not cause problems to first order, because they occur at a fixed $q^{2.}$
- However, this propagator causes a serious problem for **higher order processes**, as in the case of a two-boson exchange. Inside the square loop, conservation of energy-momentum does not limit the circulating four-momentum: any q of one boson is compensated by $-q$ of the other. To obtain the full amplitude of this process, one must integrate over this internal momentum up to infinity, and this integral **diverges**.
- The same is true for the propagator of the **virtual fermion** in the loop, a finite mass will make the amplitude diverge.
- The intrinsic mass of bosons and fermions, which destroys the gauge symmetry of the theory, thus also makes it **unusable.** Both facts are indeed intimately linked, as was shown by **t'Hooft and Veltman (Nobel Prize 1999).**
- **This is not the case, however, if** mass is a dynamical phenomenon. The Higgs mechanism invokes a scalar field to keep particles from moving at the speed of light. This way they appear massive to us.



- If massive fields are incompatible with gauge symmetry, the opposite should also be true: **symmetry breaking should make a originally massless field massive**. To understand this intuitively, we (again) use a **mechanical analogy**.
- Imagine an **infinitely fine needle**. It has no moment of inertia about its axis. Now we apply a coaxial force beyond the elastic limit of the needle. At first nothing happens, the system remains in unstable equilibrium.
- Through a quantum fluctuation, the crystal lattice of the needle weakens in a random place, and **the needle folds** in a random direction. The cylindrical symmetry of the system has spontaneously disappeared; at the same time, a **moment of inertia** about the original axis original has appeared. The system has acquired a kind of mass it did not have before.



- In a quantum field theory, a similar effect occurs if the **ground state** of a system does not posses a symmetry, that is present for the system in general.
- Let us consider a system with a **single complex field Φ**, where the minimum of energy does not match $\Phi = 0$, but occurs for all states with $\Phi^2 = v \neq 0$. The **ground state of such a system is not the vacuum**, with all fields equal to zero, but a space-time filled with Φ everywhere.
- If we want to do a perturbative calculation in such a "vacuum", we need to **choose a minimum of the energy** around which to develop the states. By choosing a specific value of Φ as ground state, with $\Phi^2 = v$, one breaks the symmetry with respect to the phase of Φ. This is called a **spontaneous symmetry breaking**.
- At the same time, the field Φ itself, and any other field interacting with it, acquires **mass**. We call such a field Φ a **Higgs field**.

How does a **particle move** in a vacuum filled with the Higgs field?

- All fields, which interact with the field Φ with a given coupling constant, are constantly kept from evolving freely. They propagate like in a **viscous liquid**. Their speed is lower than *c*, they have a mass they would not have in a "real" vacuum with $\Phi = 0$.
- **Live demonstration with test tubes filled with water and oil, smooth and rough surface balls!**
- The **mass of particles is given by their coupling constant with the Higgs field**. It is dynamically generated through interaction with this ubiquitous field.

- In the next video we will discuss the quanta of the Higgs field, the Higgs bosons.