Standard Model of Particle Physics: What's (the) matter?

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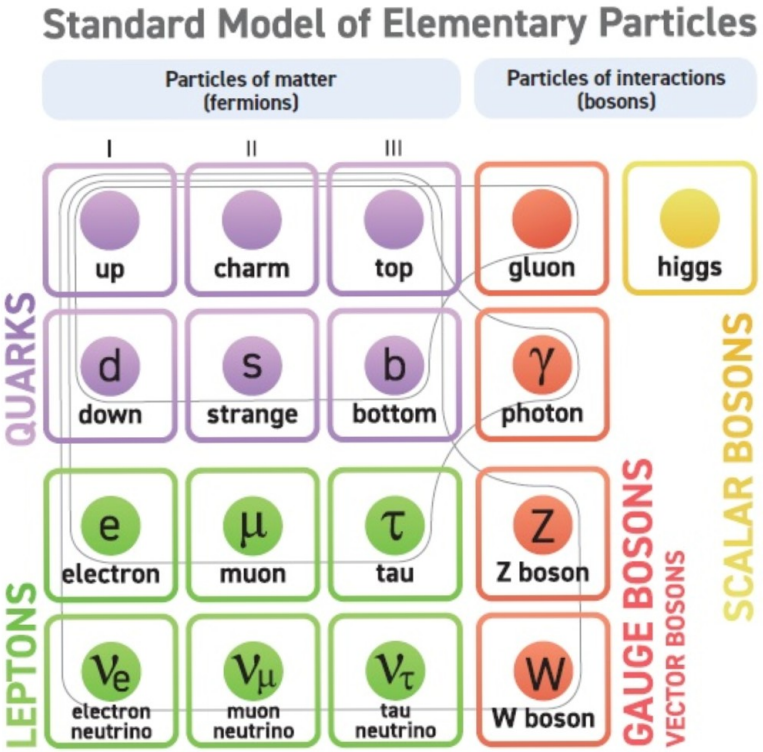
Funded by the European Union

The Standard Model.



- The Standard Model of Particle Physics is the theory that describes how particles interact with each other through three forces in Nature (EM, weak and strong)
- It consists of fundamental particles, i.e. that cannot be divided into smaller pieces, that are presented into families.
- There are 17 particles, some of them are the ones building "matter" (quarks and leptons) and the others are the mediators of the forces (vector bosons). Furthermore, there is also one Higgs boson.
- Building up and understanding the whole theory took more than 100 years (since the electron discovery to the Higgs discovery)

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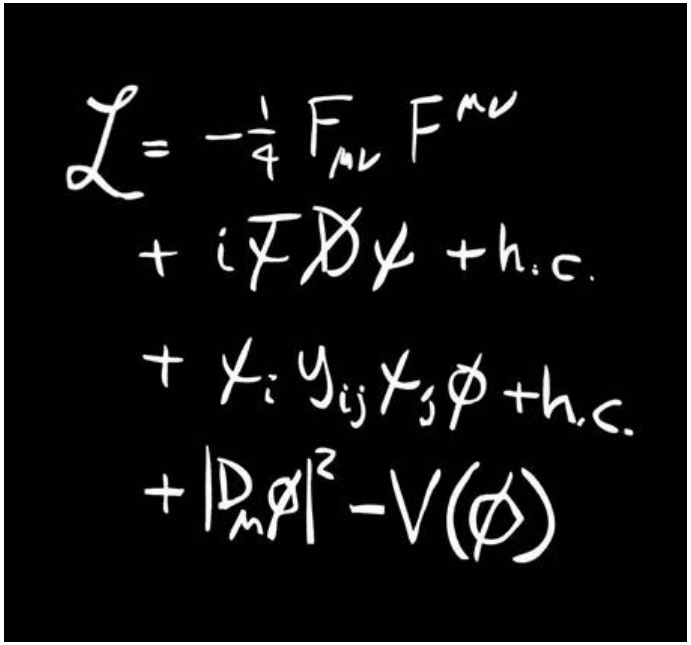

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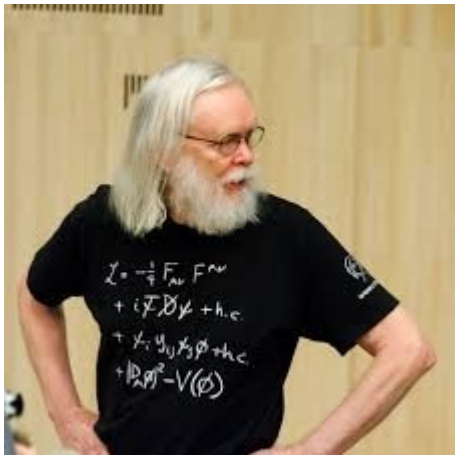

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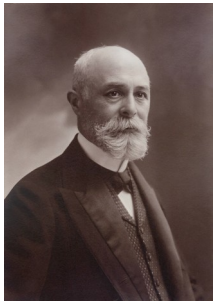
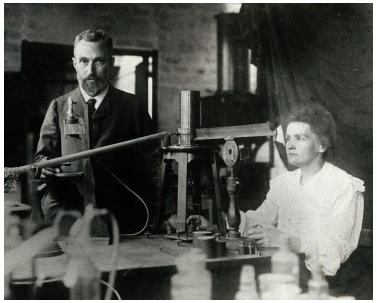
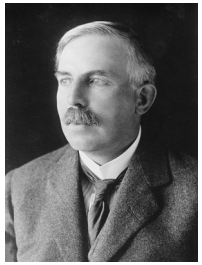
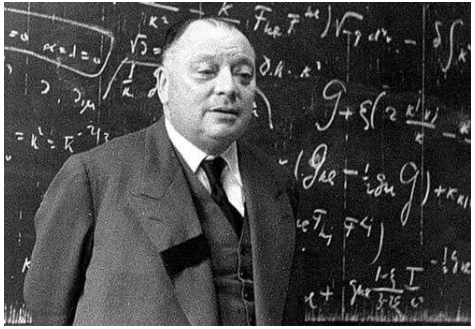
The beginning.









- The discovery of radioactivity and its properties (Becquerel, Maria Skłodowska and Pierre Curie, 1800s)

  The atom is not fundamental!

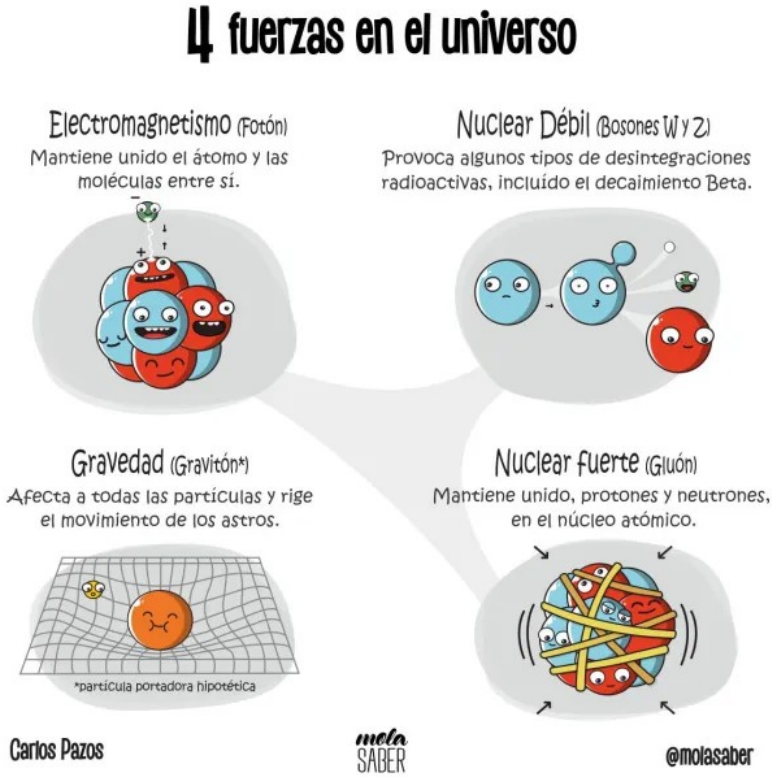
- The discovery of the atom structure. (Rutherford, 1911)

  Not only the structure of the atom but how to do modern experimental particlephysics

- The proposal of the neutrino (Pauli, 1930)

  Conservation of energy in particle interactions, how to deal with “invisible” particles.

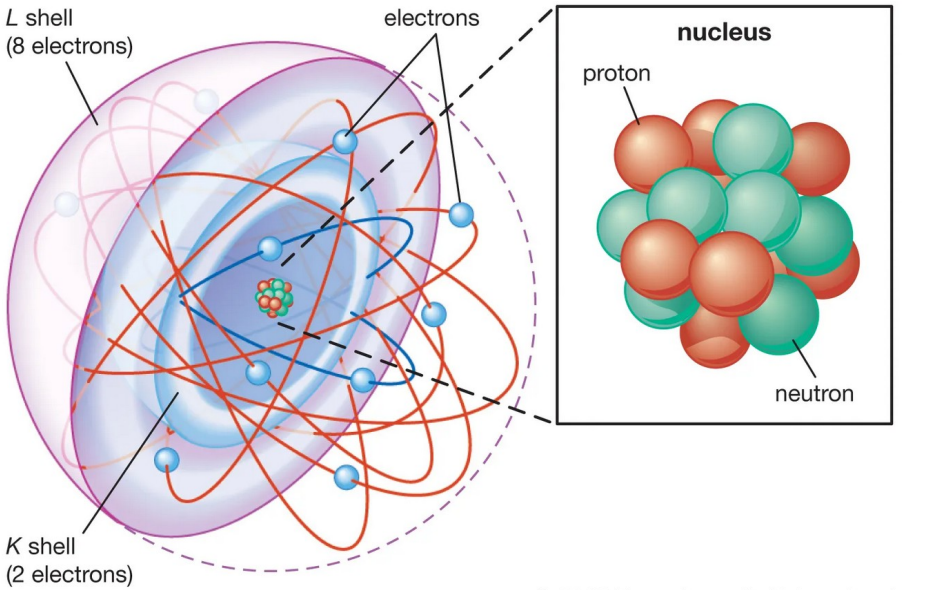
Fundamental Interactions.



- Electromagnetism: It is the interaction between particles with electric charge. E.g. the nucleus and the electron in the atom (photons)
- Weak Interaction: The responsible for some radioactive decays. Responsible of the "flavour" of the particles. (W and Z bosons)
- Strong Interaction: Keeps the protons and the neutrons inside the nucleus. (gluons)
- Gravity: Well... that is another story. (gravitons)

Strong > Weak > EM > Gravity

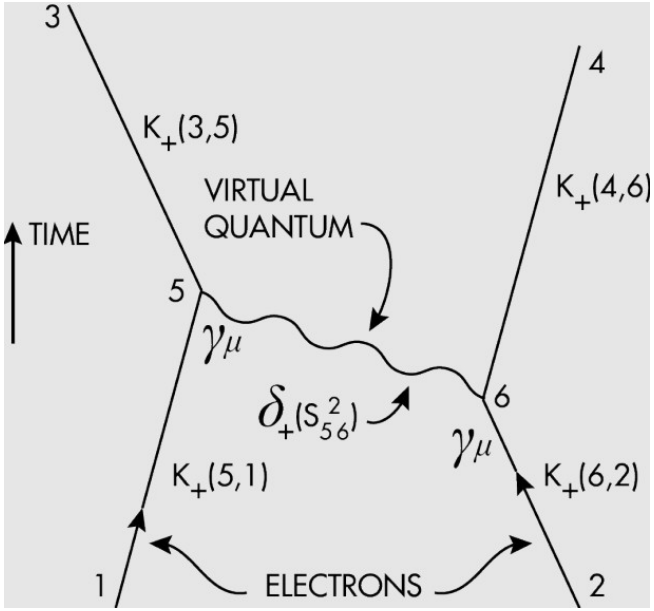
Electromagnetism.



(Disclaimer: Atoms can be different from this picture in real life)

- The atoms contain protons (+), nucleons (Ø) and electrons (-).
- The electrons describe orbits due to electromagnetic interaction
- The way these particles interact is by photons. The photon is the mediator of the electromagnetic force.
- As the photon is massless, the range of action is infinity.

Electromagnetism.

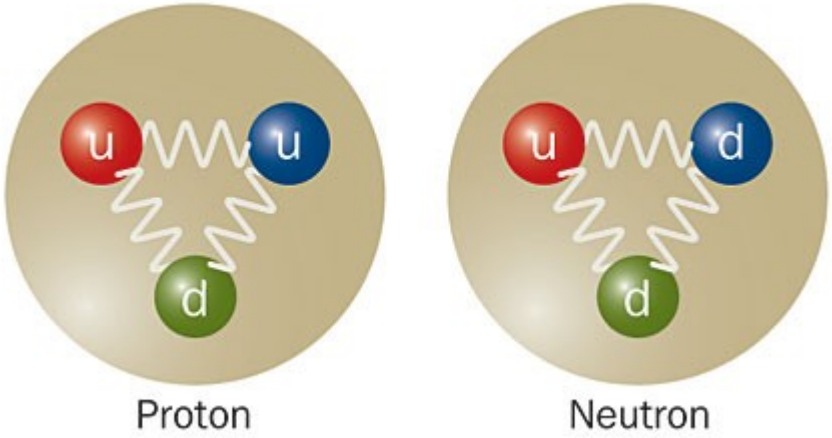


Feynman diagram of two electrons interacting through a photon.

- This is a representation of an interaction between two electrons mediated by a photon (γ)
- Feynman diagrams are pictorical representations of the mathematical expressions that describes the interactions of particles. They make our lives easier :)
- The electrons feel each other with the photon.
- The strength of this interaction is given by its coupling constant:

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c},$$

Strong Interaction.



- Protons and neutrons inside the nucleus are not fundamental: they are made up by quarks.
- The quarks are charged under the EM and the strong force. The protons interact throught the strong mediator known as the gluon.
- This way the protons can be inside the nucleus without repelling each other.
- The proton has two up quarks and one down while the neutron has one up quark and two down quarks.

Up quark: EM charge $+2/3$
Down quark: EM charge $-1/3$

Strong Interaction.

- Protons and neutrons inside the nucleus are not

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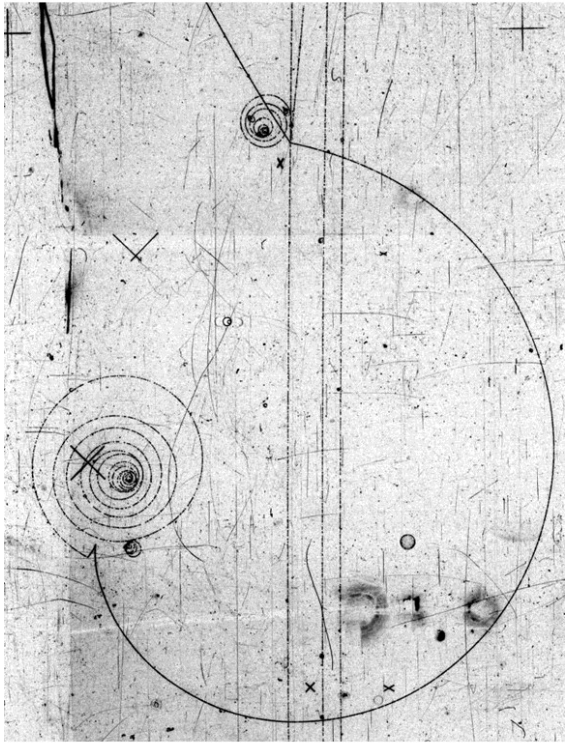
arks.

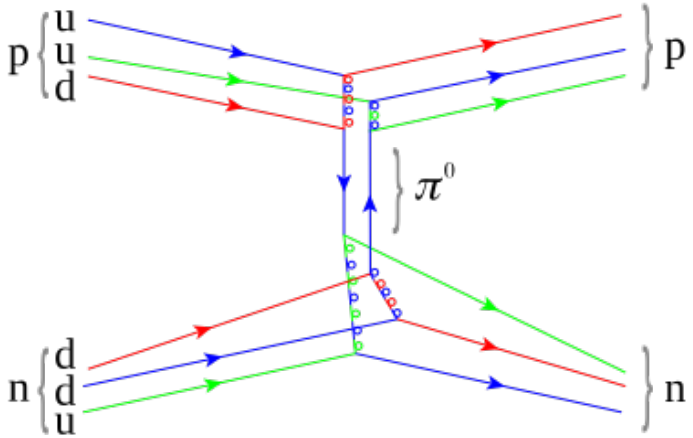
However, the strong interaction is much funnier than this

Down quark: EM charge -1/3

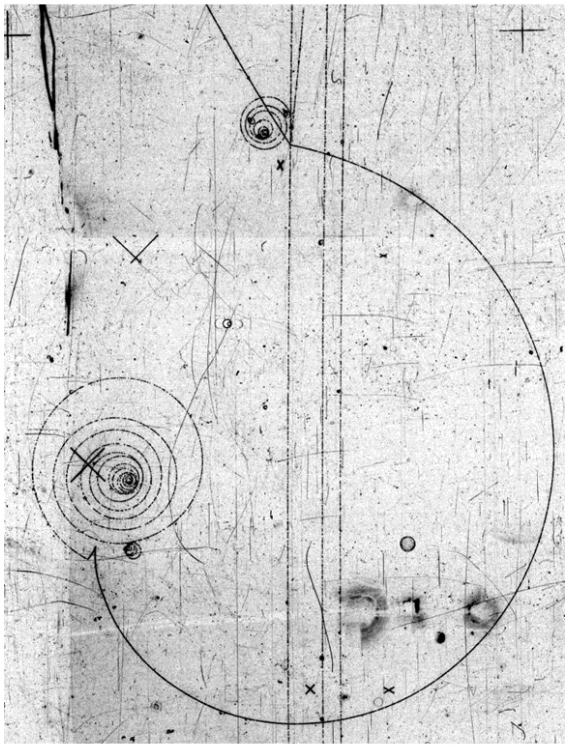
Strong Interaction.



- In 1935 Yukawa theorised the mesons as the particles that keep the nucleons together inside the nucleus.
- In 1947 and 1950 the charged and the neutral pions were discovered.

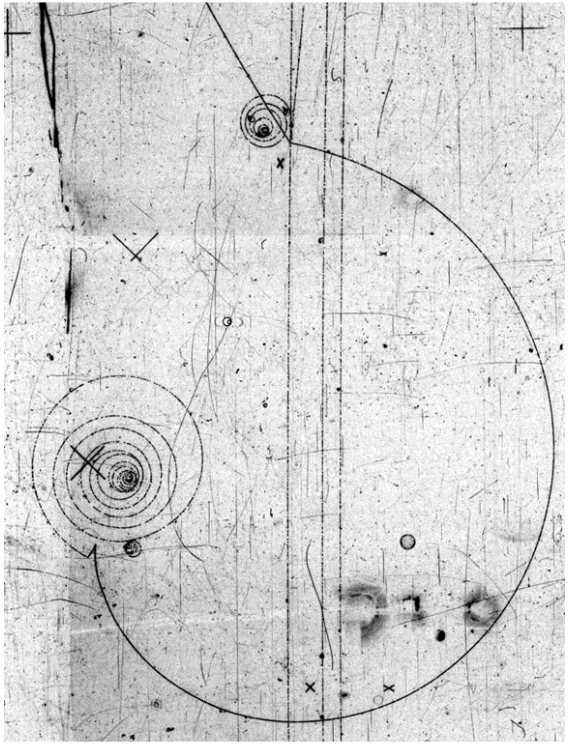


Strong Interaction.



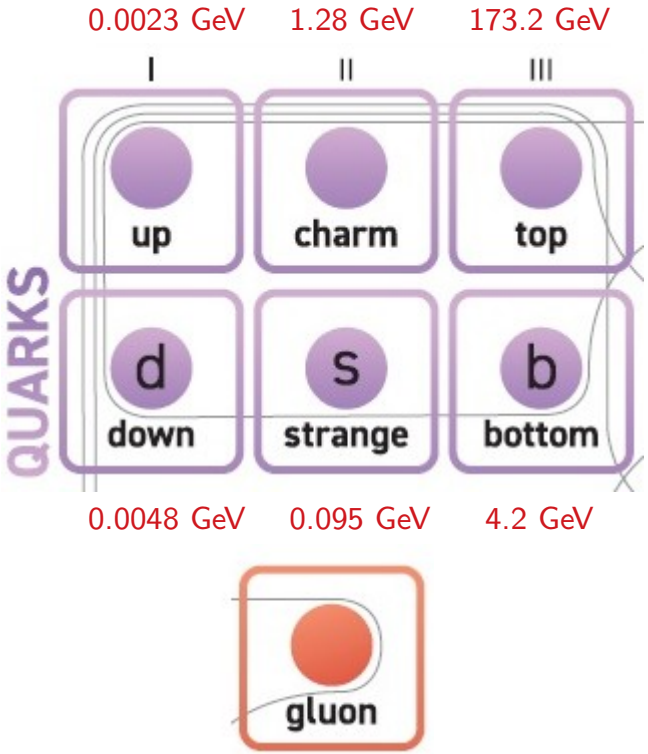
- In 1935 Yukawa theorised the mesons as the particles that keep the nucleons together inside the nucleus.
- In 1947 and 1950 the charged and the neutral pions were discovered.
- During the 50's and the 60's a particle zoo was discovered. Lots of strong particles were discovered and no one knew what they were.
- Gell-Man and Zweig proposed the quark model in 1964 in order to explain all these new particles.

Strong Interaction.



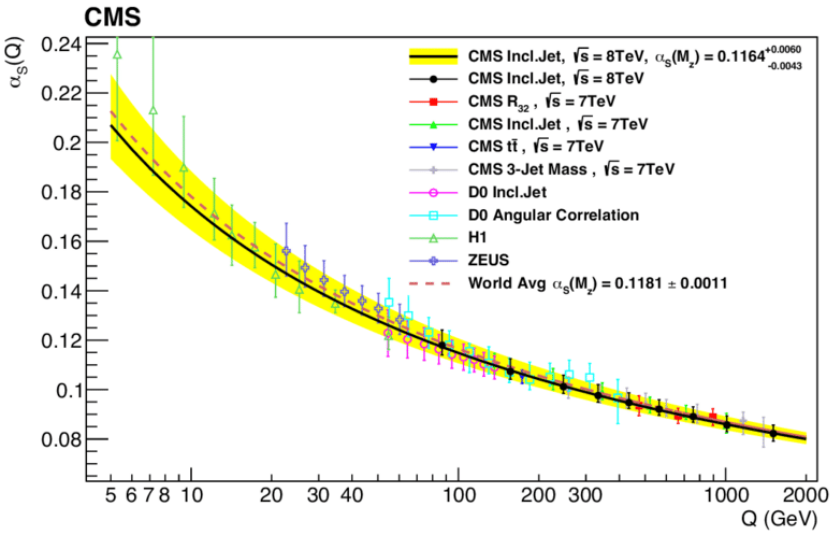
- These new particles (hadrons) were in fact made up by quarks!
  Such as the proton and the neutron.
- Mesons: Made up by two quarks
  Pions, D, K, B, η ,ρ ...
- Baryons: Made up by three quarks
  Proton, neutron, Δ, Σ, Λ, Ξ ...

Strong Interaction.



- There are 6 quarks divided in three generations.
- Each family has two generations: One up and one down quark. The difference is in the quantum numbers!
- Each generation is equal to the other except for their mass!!
- First quarks were discovered in 1969 in SLAC while the top quark was discovered in 1995 in Tevatron.
- All these quarks interact mediated by the gluon

Strong Interaction.



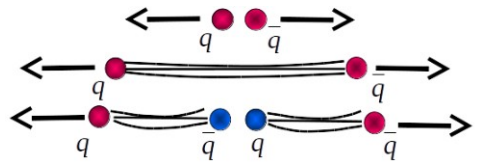
- But, why the quarks always together?

  CONFINEMENT!

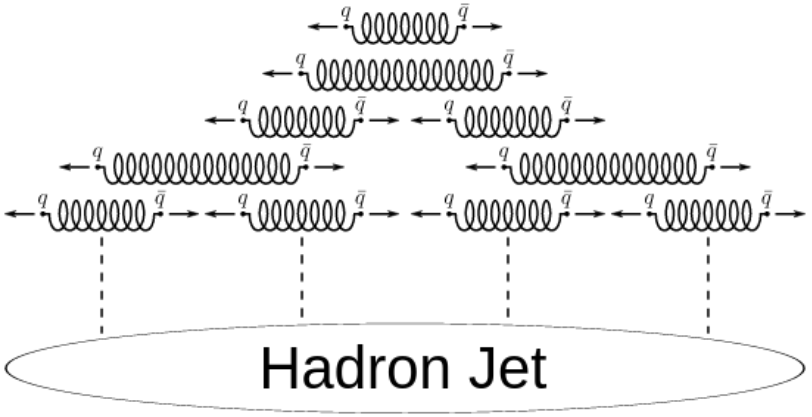
- What we know as constants are not actually constant. They change with energy!

- The strong interaction coupling is weaker with high energies, so at small distances is stronger.

Strong Interaction.



As energy decreases, hadrons (mainly mesons) freeze out



- But, why the quarks always together?

  CONFINEMENT!

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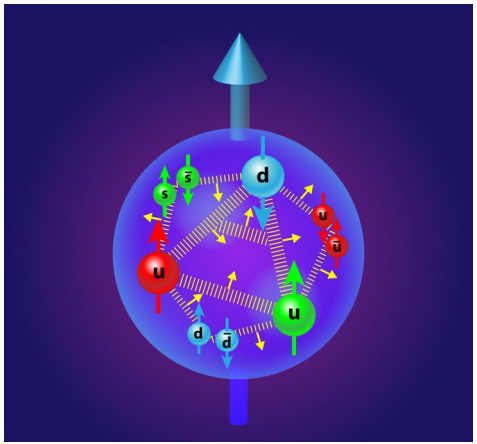
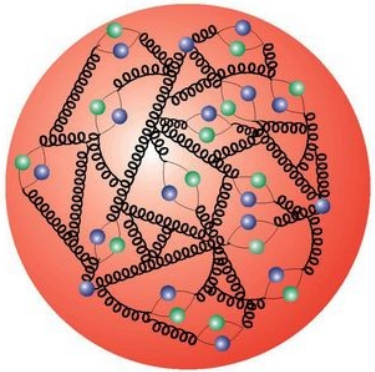
- The strong interaction coupling is weaker with high energies, so at small distances is stronger.
- When quarks are separated, pairs of new quarks are created. This originates new mesons and baryons.
- This explains why the quarks are kept together inside the nucleons.

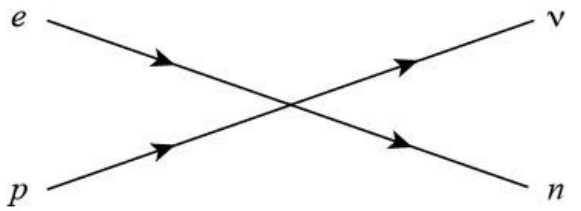
Strong Interaction.

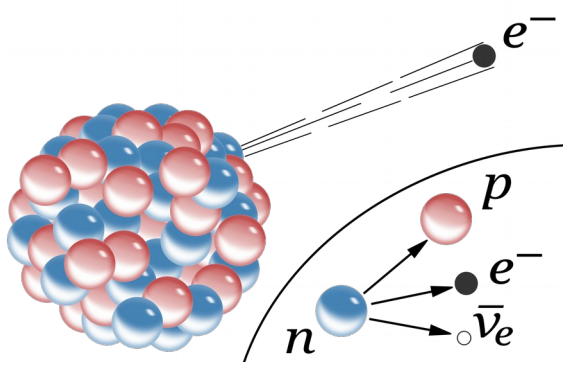




- Are there only three quarks inside the proton/neutron? Well... Yes and no.
- Inside the proton/neutron there are three valence quarks. This is what defines if it is a proton or a neutron.
- However, inside there is a sea of particles: quarks and gluons.
- The probability of finding these sea quarks and gluons will depend on the energy. At higher energies the probability is higher.
- This property is used when we collide protons at high energy since there are more gluons inside them.

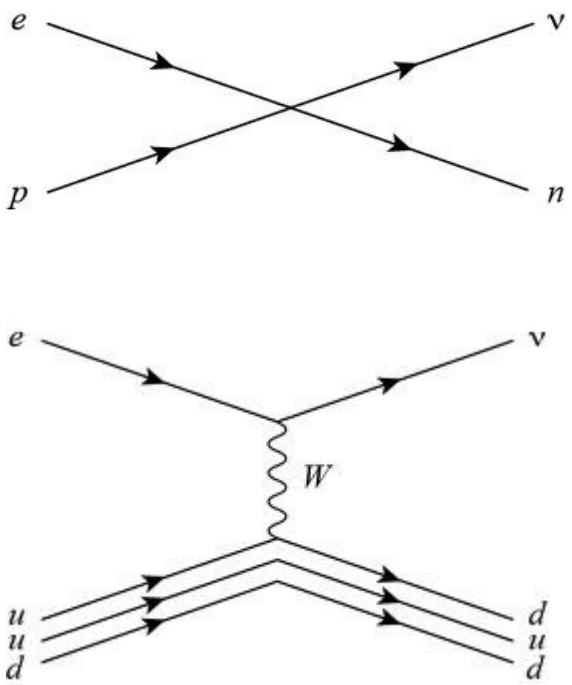
Weak Interaction.





- The weak interaction is responsible for some radioactive decays, such as the beta decay.
- In 1933 Fermi proposed a theory in order to explain this particular process.
- This theory was an effective theory describing how a neutron becomes a proton giving an electron and a neutrino.
- This seemed to work properly at low scales, but...

Weak Interaction.



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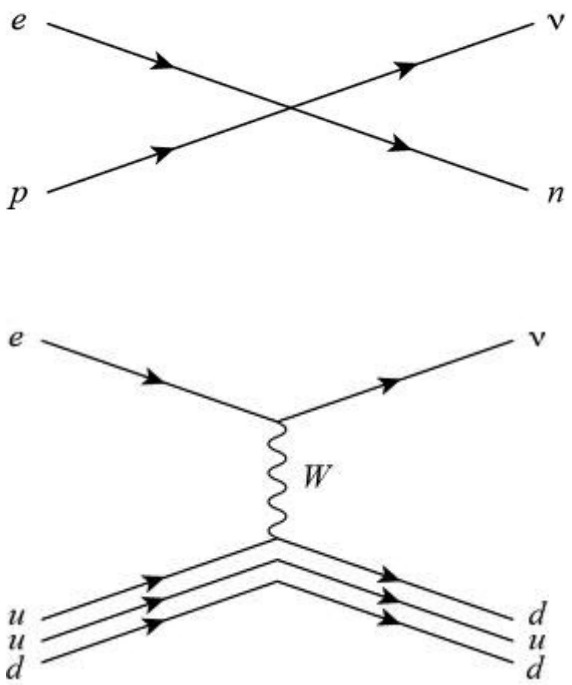
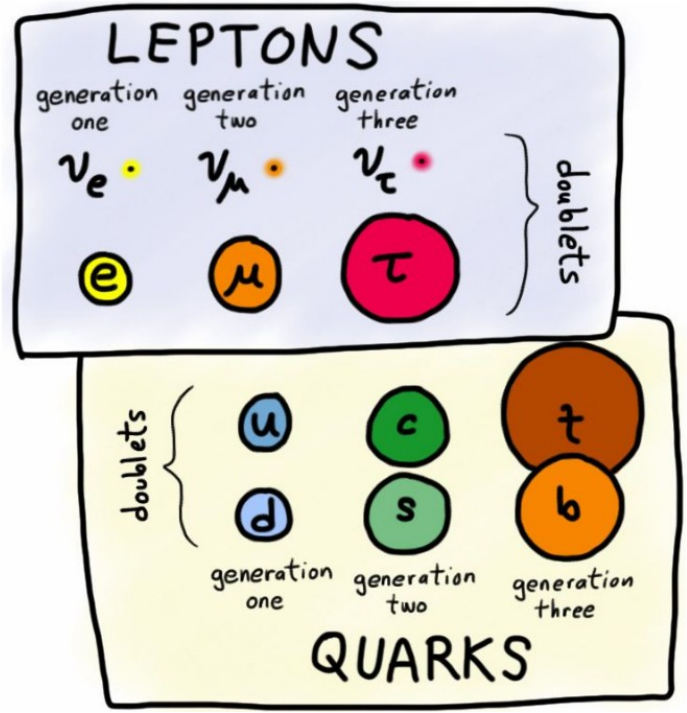
- This theory was an effective theory describing how a neutron becomes a proton giving an electron and a neutrino.
- This seemed to work properly at low scales, but... if one goes to higher energy, then it is the W vector boson the one that is the mediator of this interaction.

Weak Interaction.



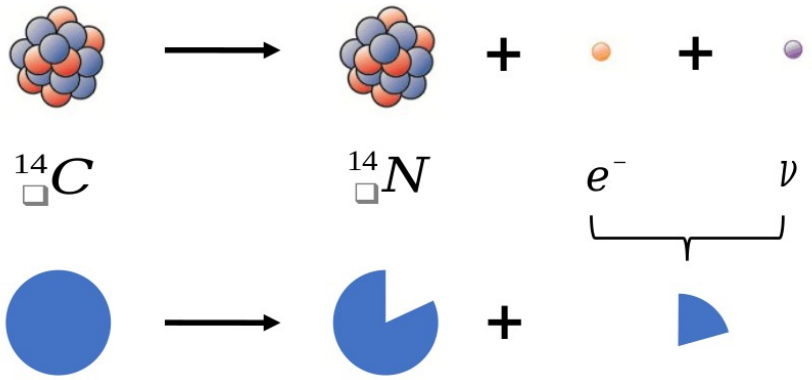
- The vector bosons of the weak interaction are the W and the Z bosons.
- The W boson has a mass of 80 GeV while the Z boson has a mass of 91 GeV.
- Both of them have a short lifetime for that reason this interaction has a short distance range.
- This interaction is often referred as flavour, but why?

Flavour in the SM.



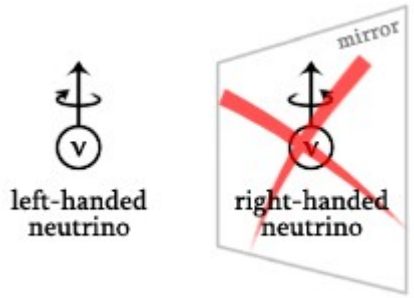
- All the matter particle that we know in the Standard Model is organized in three flavours or generations.
- Only the first generation is stable, and it is what we consider matter in the common language.
- All the copies are exactly the same except for their masses.
- According to the Standard Model the neutrinos are massless.

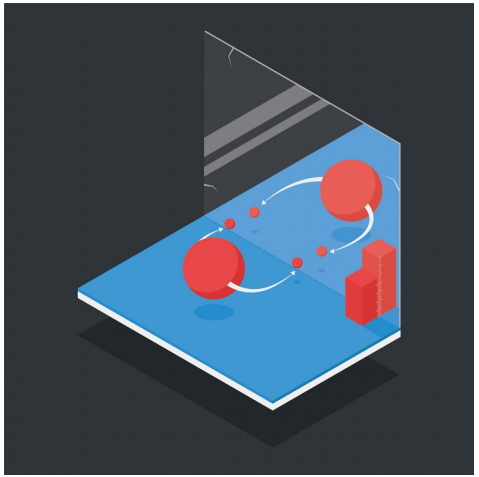
Flavour in the SM. Neutrinos.



- In certain radioactive decays there were some missing parts. If one applies the conservation of energy with the visible particles, there was some missing energy.
- Pauli predicted the existence of an invisible particle in 1930 that later was called neutrino.
- Pauli said: “I have done something very bad today by proposing a particle that cannot be detected. It is something that no theorist should ever do”
- The neutrino was discovered in 1956 in a nuclear reactor.

Weak Interaction.





- During the study of the weak interactions Chien-Shiung Wu discovered that these interactions do not conserve parity.
- Parity is a symmetry in which the equations are invariant under mirror inversions. So one reaction and its mirror reaction would have the same rate.
- Weak interaction does not conserve parity, which leads to the existence of left handed neutrinos.

ElectroWeak Interaction.

$$G \equiv SU(2)_L \otimes U(1)_Y$$

$$\psi_1(x) = \begin{pmatrix} u \\ d \end{pmatrix}_L , \qquad \psi_2(x) = u_R , \qquad \psi_3(x) = d_R$$

$$\psi_1(x) = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \qquad \psi_2(x) = \nu_{eR}$$

$$\mathcal{L} \longrightarrow g\,\overline{\psi}_1\gamma^\mu\widetilde{W}_\mu\psi_1 + g'\,B_\mu \sum_{j=1}^{3} y_j\,\overline{\psi}_j\gamma^\mu\psi_j$$

- After Wu's discovery Glashow, Shalam and Weinberg introduced the electroweak interaction.
- This theory unifies the weak and electromagnetic interactions as part of a gauge group SU(2)xU(1).
- All the particles are described as part of this group.
- However, this what not exactly what we see in nature.

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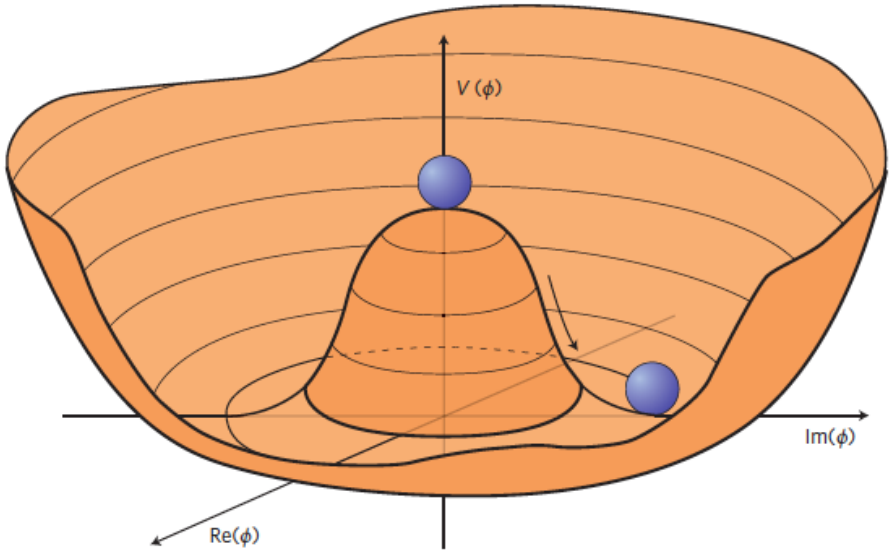
$$\begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} \equiv \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}$$

$$W_\mu \equiv (W_\mu^1 + i\,W_\mu^2)/\sqrt{2} \qquad W_\mu^\dagger \equiv (W_\mu^1 - i\,W_\mu^2)/\sqrt{2}$$

- The proposal implies a spontaneous breaking of the symmetry. $SU(2)xU(1) \rightarrow U(1)_{em}$
- This breaking would take the neutral components of W and B mixing them to give the Z and the photon.
- As only one U(1) symmetry remains there is only one massless particle, the photon. The W and Z acquire masses.
- But, what is the mechanism to give masses to this particles?

Higgs Mechanism.



- Introducing a scalar field with this kind of potential:

$$\mathcal{L}_{Higgs} = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi) \qquad V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2$$

- That interacts with the vector bosons:

$$D_\mu \phi = \left(\partial_\mu + ig\, T^i W_\mu^i + i\frac{1}{2} g' B_\mu\right) \phi$$

- If we sit on the stable minimum we can expand on its field.

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

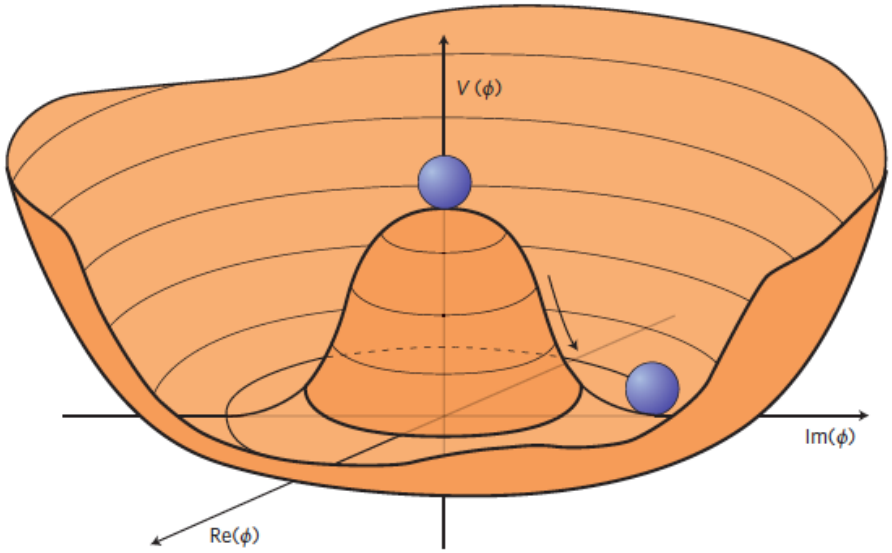
$$\begin{aligned}
(D^\mu \phi)^\dagger (D_\mu \phi) &= \left| \left(\partial_\mu + \frac{i}{2} g \tau^k W_\mu^k + \frac{i}{2} g' B_\mu\right) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \right|^2 \\
&= \frac{v^2}{8} \left| \left(g \tau^k W_\mu^k + g' B_\mu\right) \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right|^2 \\
&= \frac{v^2}{8} \left| \begin{pmatrix} g W_\mu^1 - i g W_\mu^2 \\ -g W_\mu^3 + g' B_\mu \end{pmatrix} \right|^2 \\
&= \frac{v^2}{8} \left[g^2 \left(\left(W_\mu^1\right)^2 + \left(W_\mu^2\right)^2 \right) + \left(g W_\mu^3 - g' B_\mu\right)^2 \right]
\end{aligned}$$

$$m_W = \frac{g\, v}{2}$$

$$m_Z = \frac{v}{2} \sqrt{g^2 + g'^2}$$

$$m_A = 0$$

Higgs Mechanism.



- Introducing a scalar field with this kind of potential:

$$\mathcal{L}_{Higgs} = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi) \qquad V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2$$

- That interacts with the leptons with Yukawa couplings:

$$\mathcal{L}_{Yuk} = f_e \, \bar{l}_L \, \phi \, e_R + f_u \, \bar{q}_L \, \tilde{\phi} \, u_R + f_d \, \bar{q}_L \, \phi \, d_R + h.c.$$

- If we sit on the stable minimum we can expand on its field.

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

$$\mathcal{L}_{Yuk} = \frac{f_e \, v}{\sqrt{2}} \underbrace{(\bar{e}_L e_R + \bar{e}_R e_L)} + \frac{f_u \, v}{\sqrt{2}} (\bar{u}_L u_R + \bar{u}_R u_L) + \frac{f_d \, v}{\sqrt{2}} (\bar{d}_L d_R + \bar{d}_R d_L)$$

$$m_i = -\frac{f_i \, v}{\sqrt{2}} \,, \qquad i = e, \, u, \, d \,.$$

Higgs Mechanism.

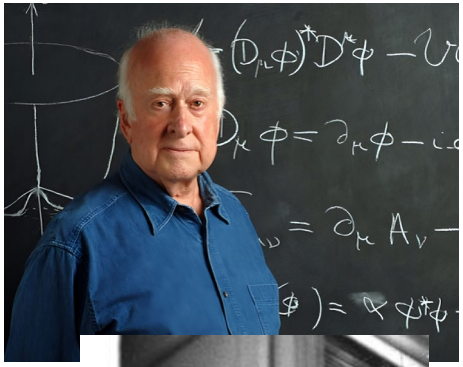
- As a result of this there is one new scalar particle

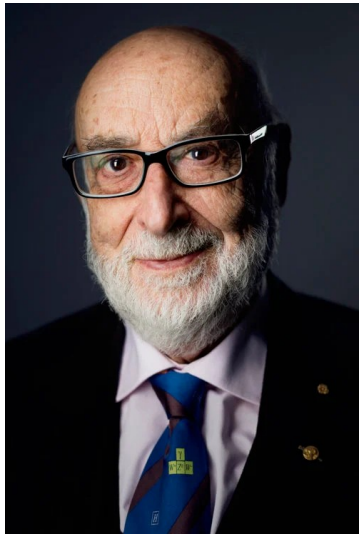
$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

that we know as the Higgs boson.

- In 2012 both ATLAS and CMS experiments found a SM-like Higgs boson with a mass of 125 GeV.

Higgs Mechanism.





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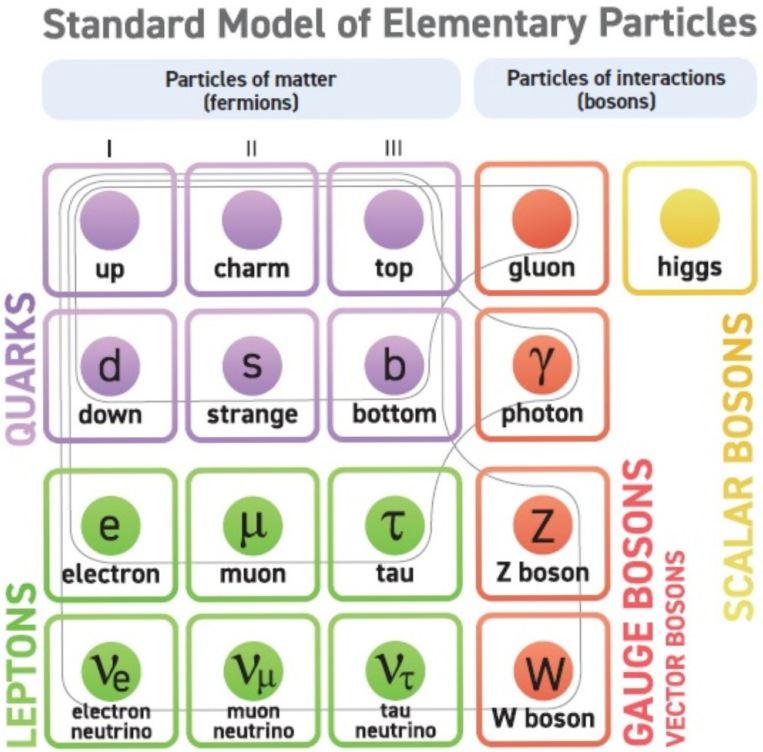
- In 2012 both ATLAS and CMS experiments found a SM-like Higgs boson with a mass of 125 GeV.

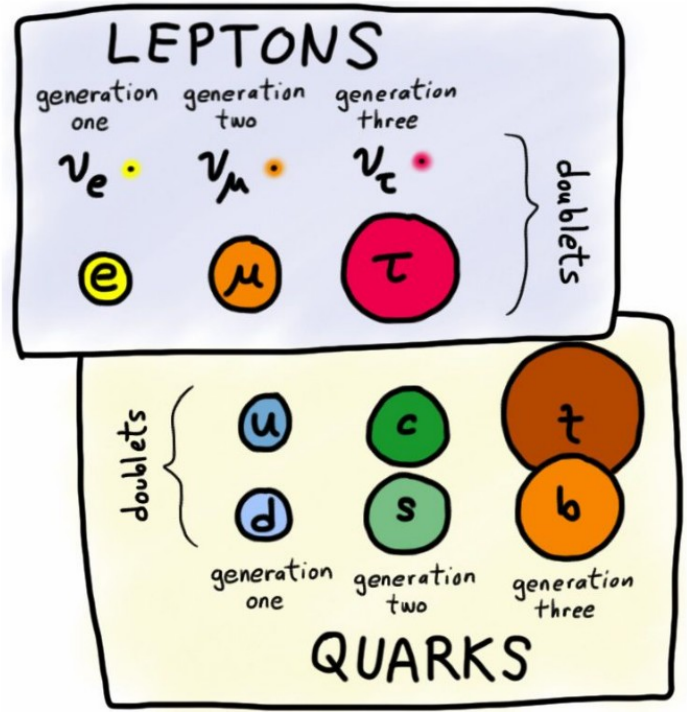
- What ended in a Nobel prize to Higgs and Englert in 2013. Unfortunately, the other physicist that should have received the prize died in 2011, Robert Brout.

The Standard Model: The final theory?



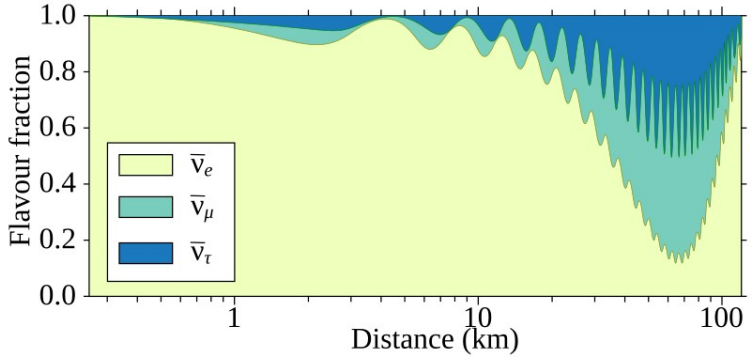
- We now know all the particle content of the Standard Model and its mathematical description using the strong and the electroweak interactions.

The Standard Model: The final theory?



- We now know all the particle content of the Standard Model and its mathematical description using the strong and the electroweak interactions.
- Why are there three families? Why not 2? 4?
- Why do they have different masses? What is the mechanism that adjust the Yukawa coupling?
- Why is the Higgs boson mass 125 GeV?

The Standard Model: The final theory?



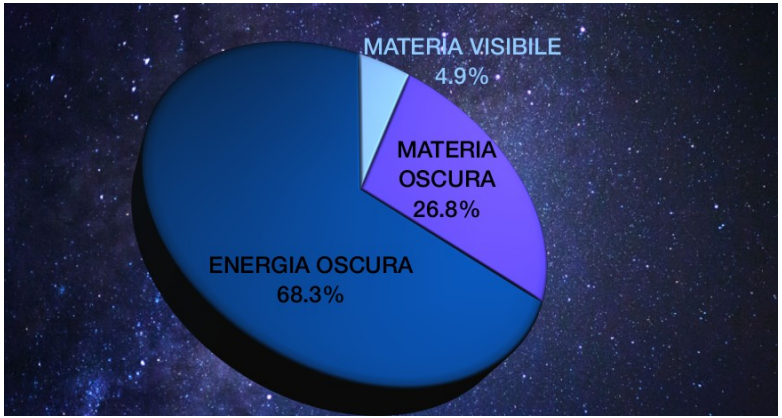
- There are other questions that arise in Nature that the Standard Model cannot answer.
- Neutrinos oscillate! That means that a neutrino produced in one flavour after some distance can oscillate to another flavour.

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle\,, \quad |\nu_i\rangle = \sum_\alpha U^*_{\alpha i} |\nu_\alpha\rangle\,,$$

$|\nu_\alpha\rangle$ electron, muon, tau. $|\nu_i\rangle$ mass eigenstates

- Neutrinos have mass!!!
- But the Standard Model as we know it do not allow neutrinos to have masses.

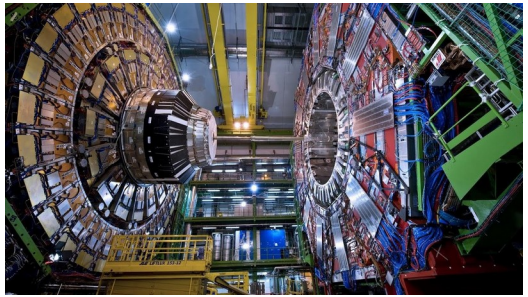
The Standard Model: The final theory?

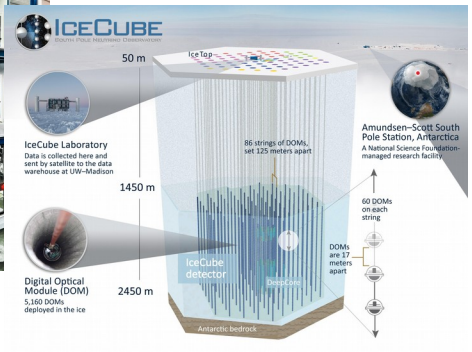


The Standard Model is not able to explain different aspects found in Nature:

- Gravity
- Dark Matter
- Matter-Antimatter Asymmetry
- Neutrino masses
- ...

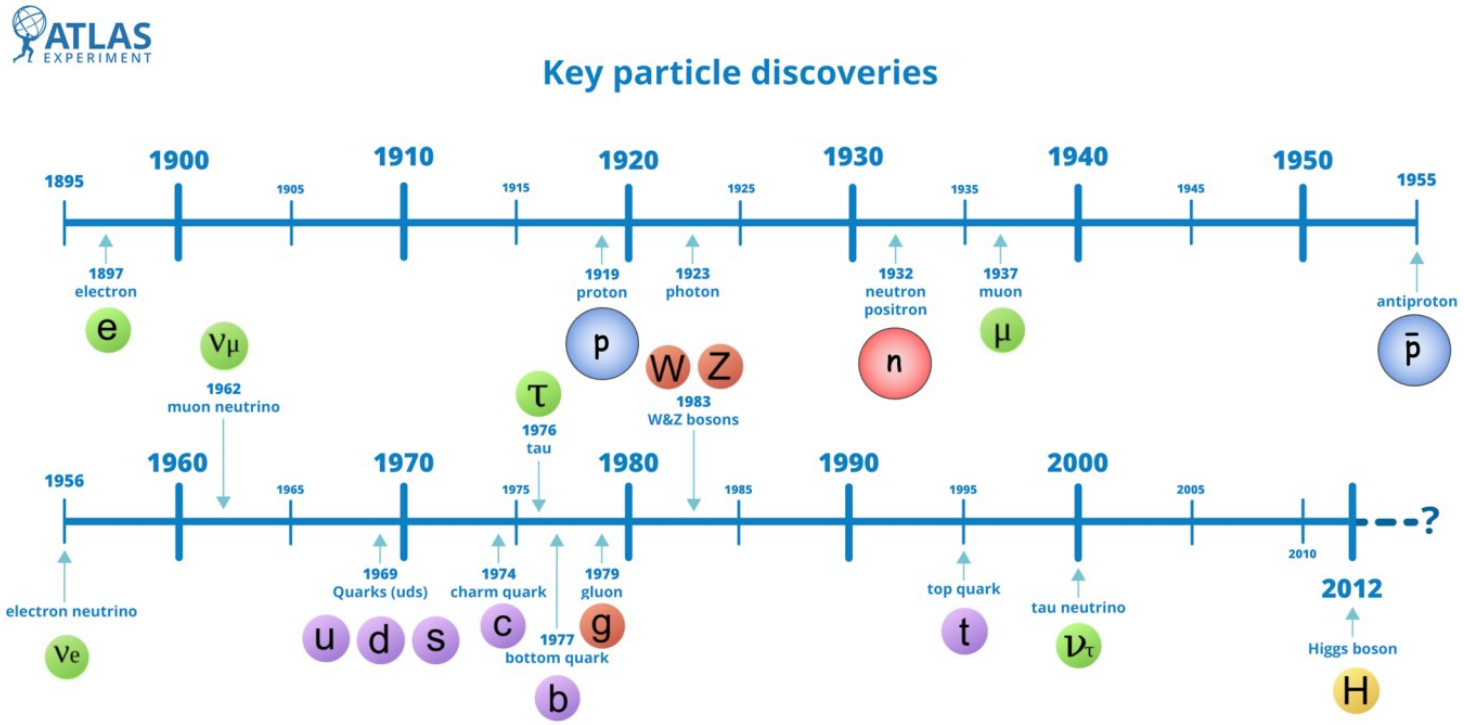
The Standard Model: The final theory?





- Different new theories that contain the Standard Model are proposed, such as Supersymmetry, Scotogenic models, extra dimensions, extra U(1) groups...
- In a parallel way, different experiments are working to unveil what can we obtain from Nature that allows us to know more about the fundamental theory that is underneath.
- There are still multiple questions that the Standard Model cannot answer.
- We are living in exciting times for particle physics.

The Standard Model: The final theory?



Thank you!