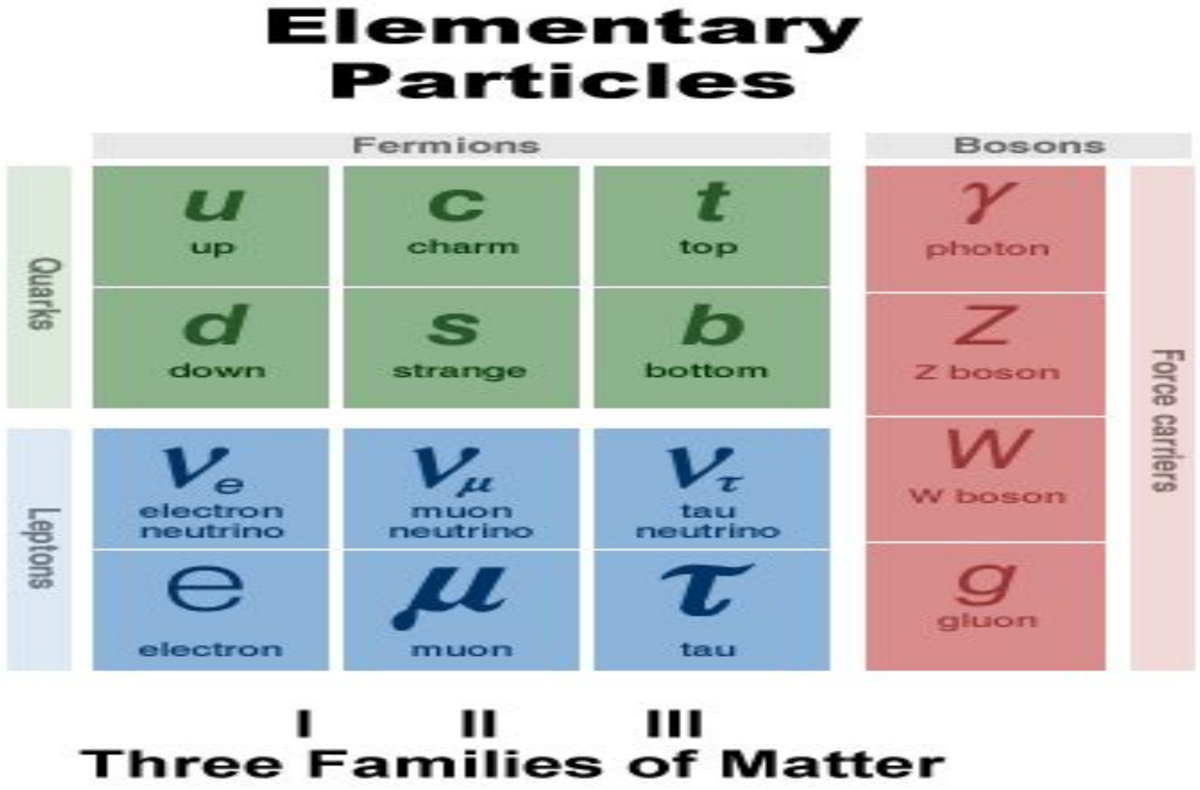
Standard Model

Summary Pic



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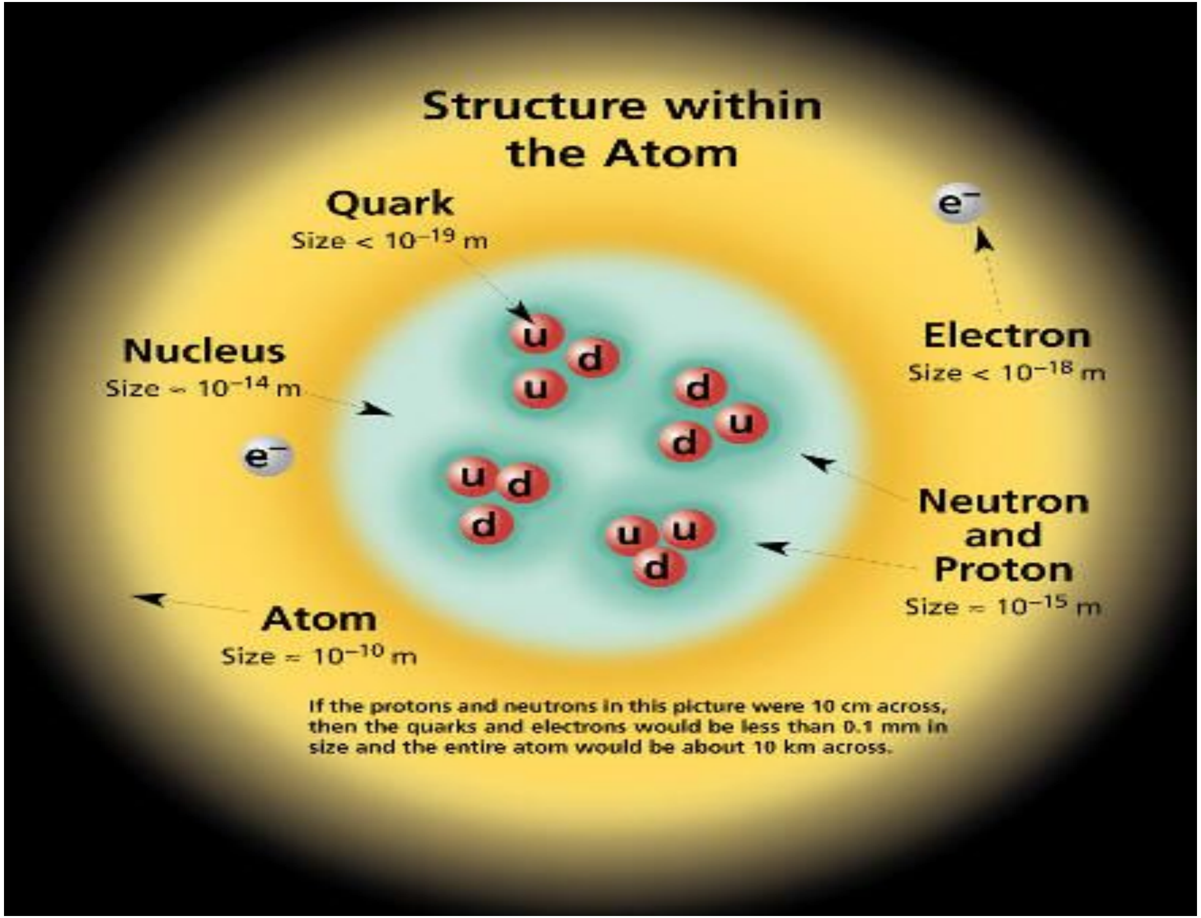

Structure within the Atom
Quark
Size < 10^{-19} m
e$^-$
Electron
Size < 10^{-18} m
Nucleus
Size ≈ 10^{-14} m
u
d
u
d
d
u
e$^-$
u
d
d
u
u
d
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Standard Model Poster

[Poster]

Force carriers

- In quantum field theory, forces are transmitted by particles, and fields are associated with particles which transmit the forces.
- The particles of the electromagnetic field are the photons. In quantum electrodynamics all electromagnetic fields are associated with photons, and the interaction between the charged particles occurs when one charged particle emits a virtual photon that is then absorbed by another charged particle.
- The photon has to be a virtual photon, because emission of a real photon would violate energy and momentum conservation. If, for example, an electron initially at rest emitted a photon, the final state would consist of an electron and a photon moving off in opposite directions, a configuration which necessarily has more energy than the initial at-rest electron.
- Particles that can interact via a certain kind of interaction continuously emit and absorb virtual particles, the force carriers for that interaction. They are surrounded by a cloud of these virtual particles. A particular force carrier particle can only be absorbed or produced by a particle which is affected by that particular force. For instance, electrons and protons have electric charge, so they can produce and absorb the electromagnetic force carrier, the photon. Neutrinos, on the other hand, have no electric charge, so they cannot absorb or produce photons.

The Electroweak Force

- Electromagnetism is the result of the unification of two forces that were initially thought to be independent, namely electric and magnetic forces. The electroweak force is the result of the unification of electromagnetism and the weak force. The weak interaction is responsible for beta decay. Beta decay produces a neutrino, which does not interact via the strong or electromagnetic force. So even though the weak force is extremely weak, it produces reactions that otherwise could not occur at all. The weak force has an extremely short range R ~ 10-18 m. Massive particles (m ~ ħ/Rc ~ 100 mproton) therefore must transmit the weak force.

- Many questions remain. Is there only one Higgs particle? It is possible to renormalize the theory with more than one additional interaction. If only one interaction is used, then the ratio of the mass of the Ws to the Z0 must have a well-defined value equal to the observed value. Most likely there is only one Higgs boson. What is its mass? There are some predictions. The measured ratio of the mass of the Ws to the Z0 should be slightly affected by the interactions of these particles with the top and bottom quarks, which depend on the masses of those quarks. This rather small effect was used to predict the mass of the top quark before its discovery in 1995. Once the mass of the top quark had been measured, the correction to the W/Z0 mass ration could be calculated exactly. A much smaller discrepancy remained. If this discrepancy is attributed to the difference in the strength of the interaction of these particles with the Higgs boson, which depends on the mass of the Higgs, a not very precise prediction of the Higgs mass can be made. This leads to a prediction of somewhere above 110 GeV, with a large uncertainty.

The Strong Force

- Our ideas about the strong force are based on the theory of quantum chromodynamics (QCD), a quantum field theory that describes interactions between quarks and a set of particles called gluons, with spin 1, that act as the carrier particles. Quarks interact via electromagnetic, weak, and strong interactions. They carry electrical charge, but all quarks, whether u, d, s, c, b, or t carry an additional, non-electrical charge, called the color charge. Similar to the electric charge being responsible for the electromagnetic interaction, color charge is responsible for the strong interaction. It is analogous to the electric charge in that, like electric charge, it is both quantized and conserved. The label for the color charge is a bit more complicated than + and -, because the color charge occurs in three different types, red, green, and blue. These labels have nothing to do with the colors of the visible-light spectrum, they merely help us keep track of the charge. In addition, for each color charge there exists an anti-color charge.

The Standard Model

- Particle physicists now believe they can describe the behavior of all known subatomic particles within a single theoretical framework called the Standard Model. This model incorporates the quarks and leptons as well as their interactions through the strong, weak and electromagnetic forces. The standard model puts the field theories QED and QCD under one umbrella. Gravity remains outside the Standard Model.

- According to the Standard Model, the basic forces are transmitted between the quarks and leptons by a third family of particles. These are called **gauge bosons**, and they differ fundamentally from the quarks and leptons, which are the building blocks of matter. There is a different type of particle for each force. Photons carry the electromagnetic force, gluons carry the strong force, weak bosons carry the weak force. A particle called the graviton is believed to be responsible for gravity, but it has not yet proved possible to build a self-consistent theory that contains the graviton. The fundamental forces appear to behave very differently in ordinary matter, but the Standard Model indicates that they are basically very similar when matter is in a high-energy environment.

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- To the extent that we can perform the calculations necessary to make a prediction and perform the experiments necessary to test those predictions, the standard model has passed every test. The standard model contains many parameters whose origins and values one would like to understand more deeply. In this way, the standard model sets out a firm platform from which searches for "new physics" can be launched. The standard model is not really a single theory of both electroweak and strong forces as much as it is a way to bring these two theories together under a single umbrella. One important aspect of the standard model is that the theories of electroweak and strong forces are constructed in identical ways. There are of course differences. These differences lead to massive carriers for the weak interactions, massless carriers for the electromagnetic and strong interactions, and to confined gluons and quarks. Yet in many ways there are more similarities than differences, and these have led to attempts to construct a single unified theory.

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- The Standard Model still contains many arbitrary parameters that come from experiments. In the Standard Model, the quarks, leptons and gauge bosons acquire their masses through a mechanism devised by Peter Higgs of Edinburgh University. According to this mechanism, particles interact with a new particle, known as the Higgs boson, and it is the strength of this interaction that gives the particles their masses. The gauge bosons, which transmit the fundamental forces, are a manifestation of the fields associated with those forces. In the same way, the Higgs boson is also the particle of a field. However, this field has different properties from the others, in particular it gives rise to mass. As yet we have no experimental evidence for the Higgs boson. This is a missing link in the Standard Model, which otherwise stands up to very precise and stringent tests. A major task for particle physics in the years to come will be to search for the missing ingredient, be it the Higgs boson or maybe something else, that underlies the origin of mass.