Lecture 26

Fundamentals of Physics

Phys 120, Fall 2015

Quantum Fields

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Overview

- Quantized Fields: the reason for particles
- Quantum Electrodynamics: the strange theory of electrons and light
- Antimatter
- Electroweak unification and neutrinos
- The Strong Force and Quarks
- Quantum Gravity: Physics and the Planck scale

Seeing particles

We saw that it is normally impossible to see small particles like atoms, α-particles, let alone electrons and protons.

Can you think of any way of making them visible, not only in one instance, as in a photographic film, but showing a full path of a particle?

The Cloud chamber

Charles Thomson Rees Wilson (1869 – 1959), a Scottish physicist, was fascinated by optical phenomena in clouds while he was climbing Ben Nevis.

He tried to build miniature clouds in his laboratory by generating air that was saturated with water, and then cooling the air by expanding the container. This mixture was then ready to condensate.

What he noticed is that something left path in his chamber!

When you click on the title, you will see a wikipedia page that contains a movie of an operating cloud chamber.

The reason is that highly energetic particles will ionize the air, and the ions act as nucleation sites for little water drops, that are visible as cloudy path.

Particles in a cloud camber

One can learn more about these particles by applying an magnetic field, as such a field will bend the path of electrically charged particles.

Some of the particles that can be detected this way can be easily identified: α-particles leave broad traces, electrons leave thinner path.

But some particles don't look like particles that were known before. There was an electron with a positive charge, there were pairs of particle seemingly created out of nothing, and other strange particles were detected. And for a while it looked like there was no end to the new discoveries.

Quantum and relativity

Quantum and relativity were both developed at the beginning of the 20th century. But both theories are not consistent, i.e. we don't have a theory for small, fast moving particles.

A theory that combines quantum theory and special relativity was developed in the 1930s. It is called **Quantum Field Theory**. (One part, quantum electro dynamics is the most accurate theory ever invented). Like most of Physics it is basically simple, but it takes a little getting used to.

Underlying it is the **field view of reality**.

Quantized Fields: The reason for particles

A **field** (E,B,grav, matter) is spread out over a region of space. The region does not need to contain any "things" at all. A field is a condition of space. Think of a magnetic field: it describes the possibility of feeling a force, regardless if anything actually experiences the force. But fields do contain energy, so they are real, not mere mental constructions.

The core idea of Quantum Field Theory is that the world is only made up of fields. All fields obey the rules of quantum mechanics and special relativity.

Remember the EM field: it reacts only in a quantized form, and we called the quanta photons. Similarly matter fields have quanta that we call electrons, protons, neutrons, atoms etc.

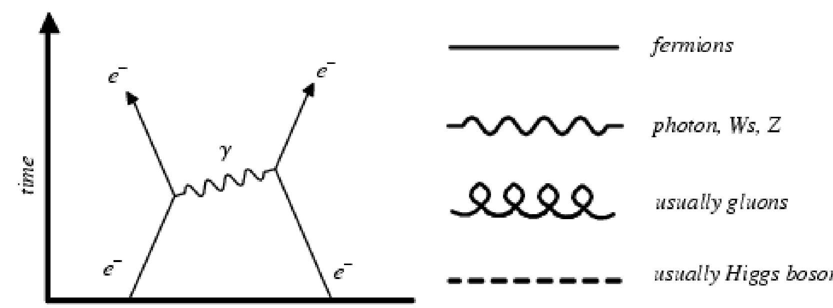
We will now learn that there are other kinds of radiation quanta, similar to photons, and other kinds of material quanta like electrons and protons.

The Quantum Theory of Fields

The essential reality is a few fields, such as the EM field, that fill the universe and that obey the principles of quantum physics and special relativity. Everything that happens is nature is a result of changes in these fields. Quantization requires that, whenever an interaction occurs, these fields must exhibit themselves as bundles or quanta of field energy. All of nature's particles of radiation and matter are quanta of this sort.

Quantum Electrodynamics: the strange theory of electrons and light

Developed by Shin'ichiro Tomanaga, then independently by Feynman and Schwinger.
Quantum electrodynamics describes the interaction between quantized EM fields, and quantized **electron fields**. Because the theory has to obey both quantum physics and special relativity it takes on a very special mathematical form which in turn leads to unexpected predictions.
We follow Feynman's description who used the enigmatic Feynman diagrams to describe what happens: in this picture electrons interact by exchanging photons. For a particle to be **electrically charged** means that it has the ability of emit and absorb photons.



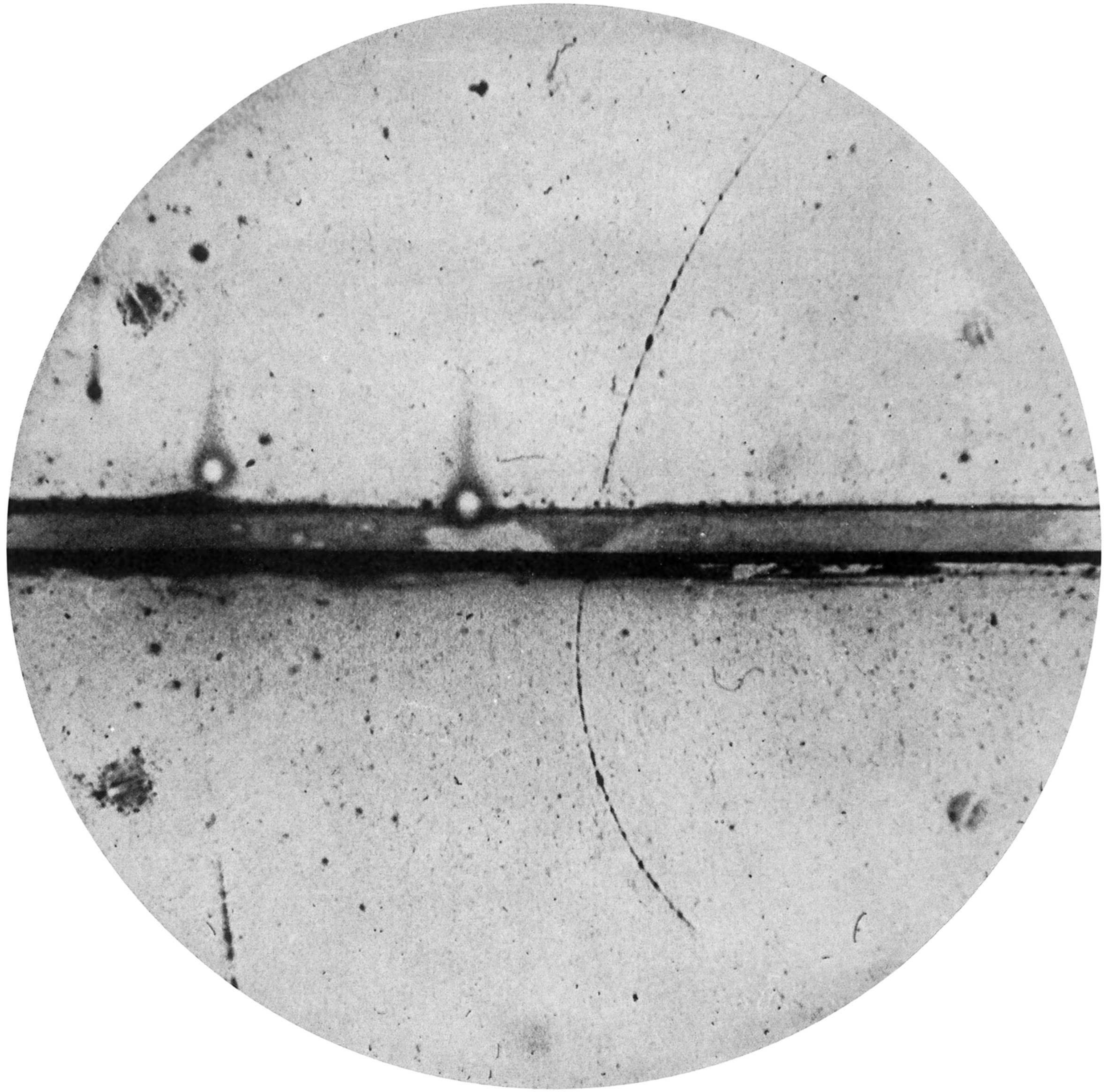
Time reversal symmetry – the positron

When write down a theory that obeys quantum mechanics and special relativity another strange thing happens: the theory predicts a new kind of particle!

This particle must be just like an electron, but with the opposite charge! In Feynman's language this is an electron moving backward in time. This positive electron, the **positron** had to exists to make his theory obey time-reversal symmetry.

This particle was experimentally found in 1932 by Anderson in a cloud chamber! He was looking at cosmic rays and found a particle that behaved like an electron with the opposite charge.

Positron discovery: a photo wins a Nobel price!

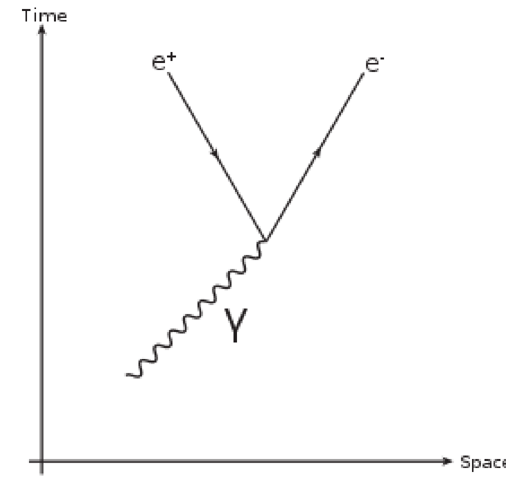


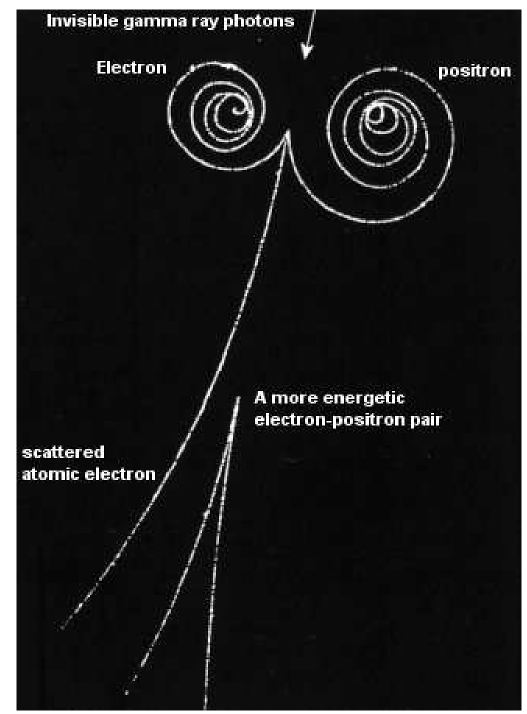
Discovery of more particles

Examining more cosmic radiation Anderson found another particle that was like an electron, but it was not held back by a lead plate that should have kept back any particle as light as an electron.

He had discovered a new particle that was just like the electron, but 200 times more massive. This new particle was called a **muon**.

Antimatter

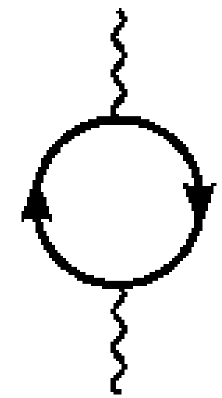




Quantum field theory requires that for any particle, an equivalent **antiparticle** also exist. We have already encountered anti-electrons which we called positrons. But there are also **anti-protons**, **anti-neutrons**.

A profound prediction of QFT is the **creation and anihilation of matter**. An EM field can give up one quanta and generate two particles in the electron field: there have to be two quanta since the total charge needs to be conserved. We then get an electron and a positron.

Heisenberg: *The discovery of particles and antiparticles has changed our whole outlook on atomic physics . . . As soon as one knows that one can create pairs, then one has to consider an elementary particle as a compound system; because virtually it could be this particle plus a pair of particles, plus two pairs of particles and so on, and so all of a sudden the whole idea of elementary particles has changed. up to that time I think every physicist had thought of the elementary particles along the lines of the philosophy of Democritus, namely by considering them as unchangeable units which are just given in nature and are always the same thing, they never change, they never can be transmuted into anything else. They are not dynamical system, they just exist in themselves. After this discovery everything looked different because one could ask, why should a photon not sometimes become a photon plus an electron-positron pair and so on? . . . Thereby the problem of dividing matter had come into a different light.*



Antimatter

The existence of antiparticles implies the existence of **antimatter**, similar to normal matter but made up of anti-particles. In 1996 the first anti-hydrogen was created in a laboratory.

Does anti-matter exist in nature? It would be possible to imagine whole galaxies made up of anti-matter, but when such a galaxy would collide with a matter galaxy large amounts of radiation would be created that should be visible to us. We have observed many galaxy collisions, but none appear to be of a matter - antimatter galaxy collision type. Therefore we believe that there are no large amounts of antimatter in the universe.

Why matter and not antimatter?

If Physics is symmetric, why did the Big Bang not create both matter and antimatter? It is believed that it did, but that just a tiny amount more matter than antimatter was created. And that is all that is left now.

Concept Check

If you visited an antigalaxy,

a) you would be pulled into its black hole and ripped apart;

b) any planets there would contain many of the same chemical elements as Earth but the would be made of antimatter;

c) you would find gravity to be repulsive rather than attractive;

d) you would be annihilated;

e) it would definitely be a one-way trip.

Concept Check

A certain gamma-ray source emits photons that have a 20% chance of being found as an electron-positron pair. The source emits 400 photons. How many individual material particles will be found?

a) Approximately 160
b) exactly 160
c) approximately 80
e) exactly 80

Concept Check

Which of these feels the electric force?

a) proton

b) electron

c) positron

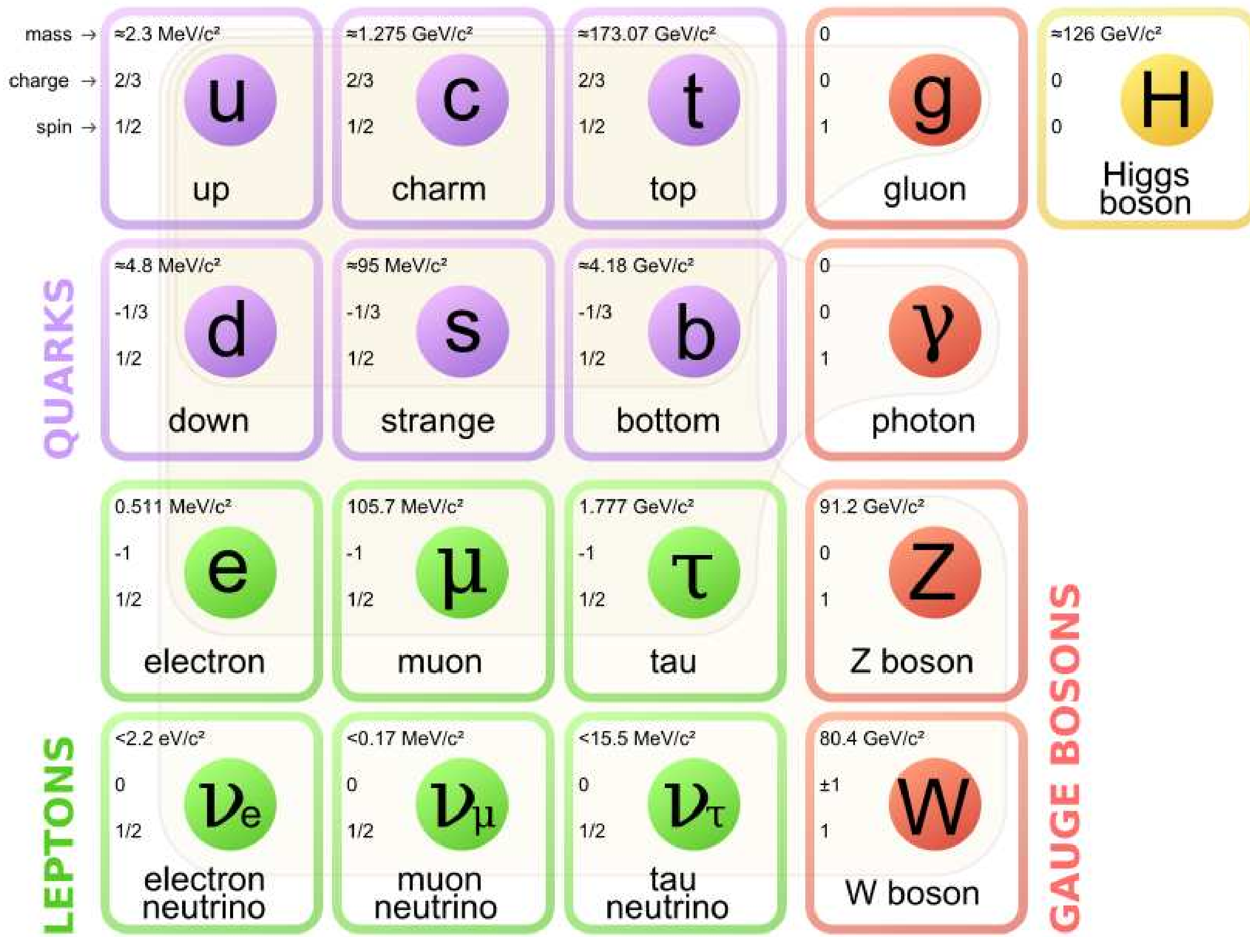
d) antiproton

Three generations of particles

In 1967 another electron-like particle was observed, the **tau**. It is much heavier than the muon, about 3500 eletron masses, or nearly twice as much as a proton.

Now we have three generations of electron like particles. Are there more? As we will see, the answer is no.

The Standard Model



This are all the particles we believe make up the universe. For each Quark and Lepton there is an antiparticle. We have talked about:
Electron: e
Positron: $\bar{e}$
Muon: μ (heavy electron)
Proton: $p = duu$
Neutron:$n = ddu$
FORCES:
Electromagnetic: γ (photon,light)
Weak : Z, W
Strong nuclear: g
Neutrino: ν.
Higgs Boson gives mass to particles

Many other particles are observed, like
pions $\Pi^+ = u\bar{d}, \Pi^- = \bar{u}d, \Pi^{=} u\bar{u}, d\bar{d}$

Why haven't you heard about pions?

Many of these "exotic" particles are unstable and will decay. In the case of pions we have

$$\Pi^- \to \mu^- + \bar{\nu}_\mu$$

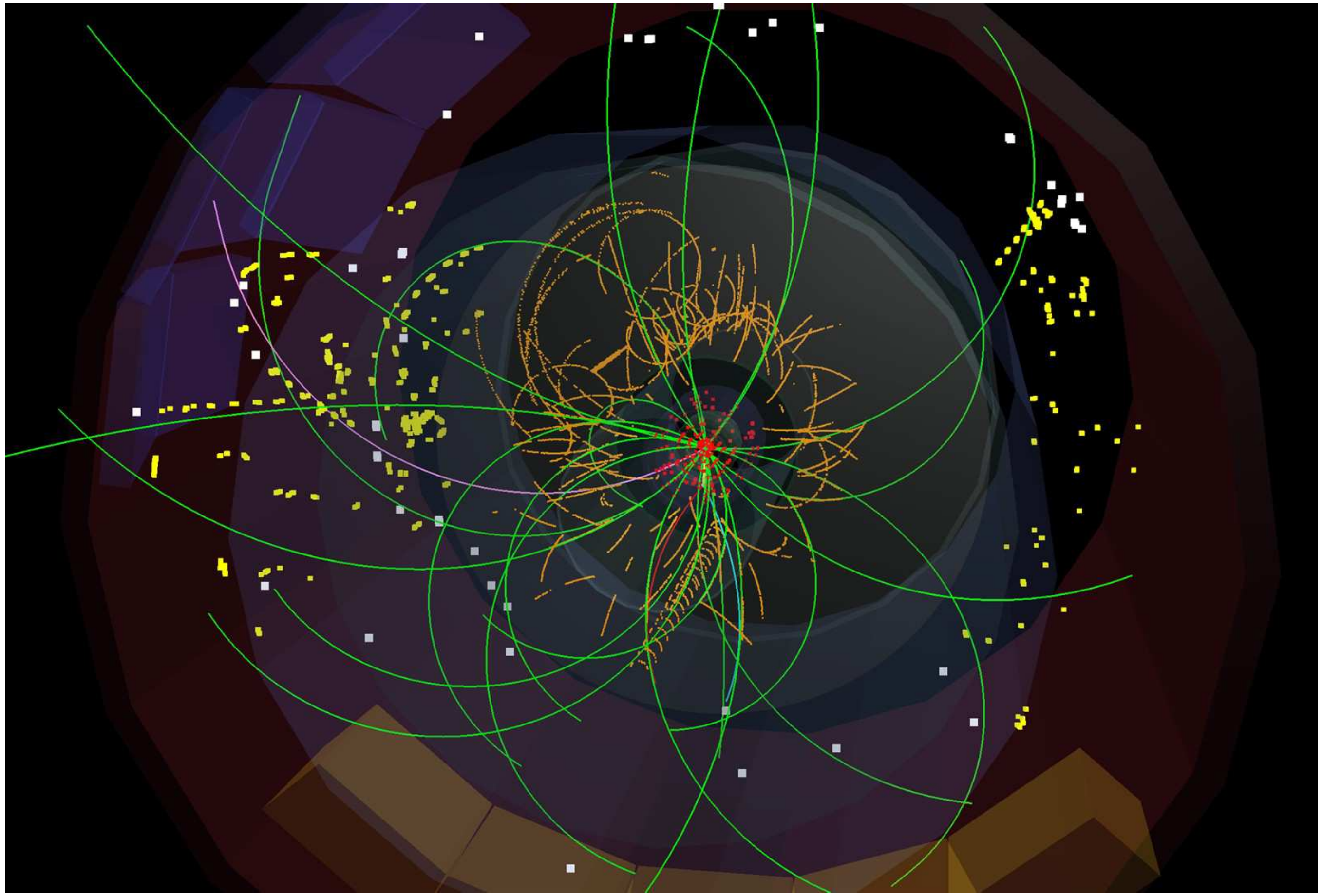
with a half life of 2.6 $10^{-8}s$. The muon is itself an unstable particle and it will also decay

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

with a half-life of about 2 $10^{-6}s$. The neutrino story is even more interesting, and it turns out that neutrinos change flavor with time, a phenomenon known as neutrino oscillations.

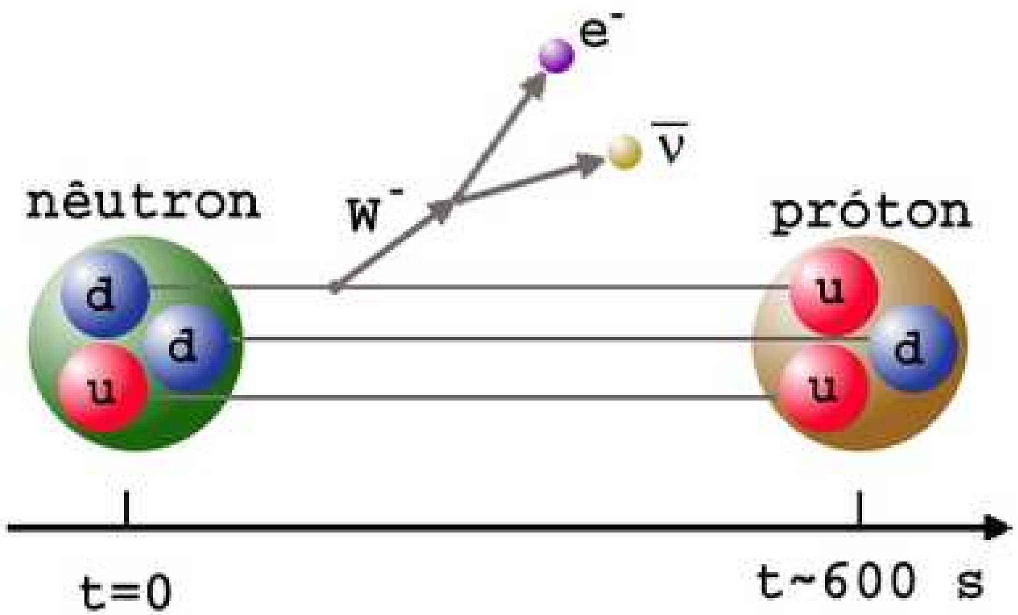
LHC - Large Hadron Collider

At Cern protons are accelerated to 0.99999998 times lightspeed and are brought together in a head-on collision. The resulting event causes all kinds of strange and wonderful particles to be created:



Neutron decay

With the standard model we can now also describe what happens to a free nutron:



A free neutron has a half-life of about 10 minutes, but when it is in a nucleus, then it is stable.

Non-existence of “empty space”

QFT has a strange view of **vacuum**. Quantum uncertainties require fields to fluctuate around their long-time average values. These **energy fluctuations** cause the short-lived creation of particle-antiparticle pairs. This can change the electric properties of the vacuum, and this caused theorists to predict that some energetic states in atoms have a slightly shifted values. This is known as the **Lamb shift**.

It was measured and verified with uncanny accuracy!

Gravity

If you payed close attention, you may have noticed that we missed gravity in our discussion of forces in Quantum Field Theory.

How one includes gravity in a consistent "theory of everything" is still an outstanding question.

Summary

Experimental physicists discovered a “zoo” of new particles.

Theorists developed quantum field theories that describe the fundamental set of constituents, three families consisting of two quarks (charge -1/3 and 2/3), and an electron like particle with its neutrino.

Interactions between these particles is mediated by photons (electromagnetism), gluons (strong interaction) and W- and Z- bosons for the weak force.

For each particle there is an antiparticle.

This abstract theoretical framework gave a “simple” description of the particle zoo, and also gives the most accurate theoretical predictions (in the case of Quantum Electro Dynamics).

This leads to the view of a very dynamic world, constantly undergoing change.

Conclusion

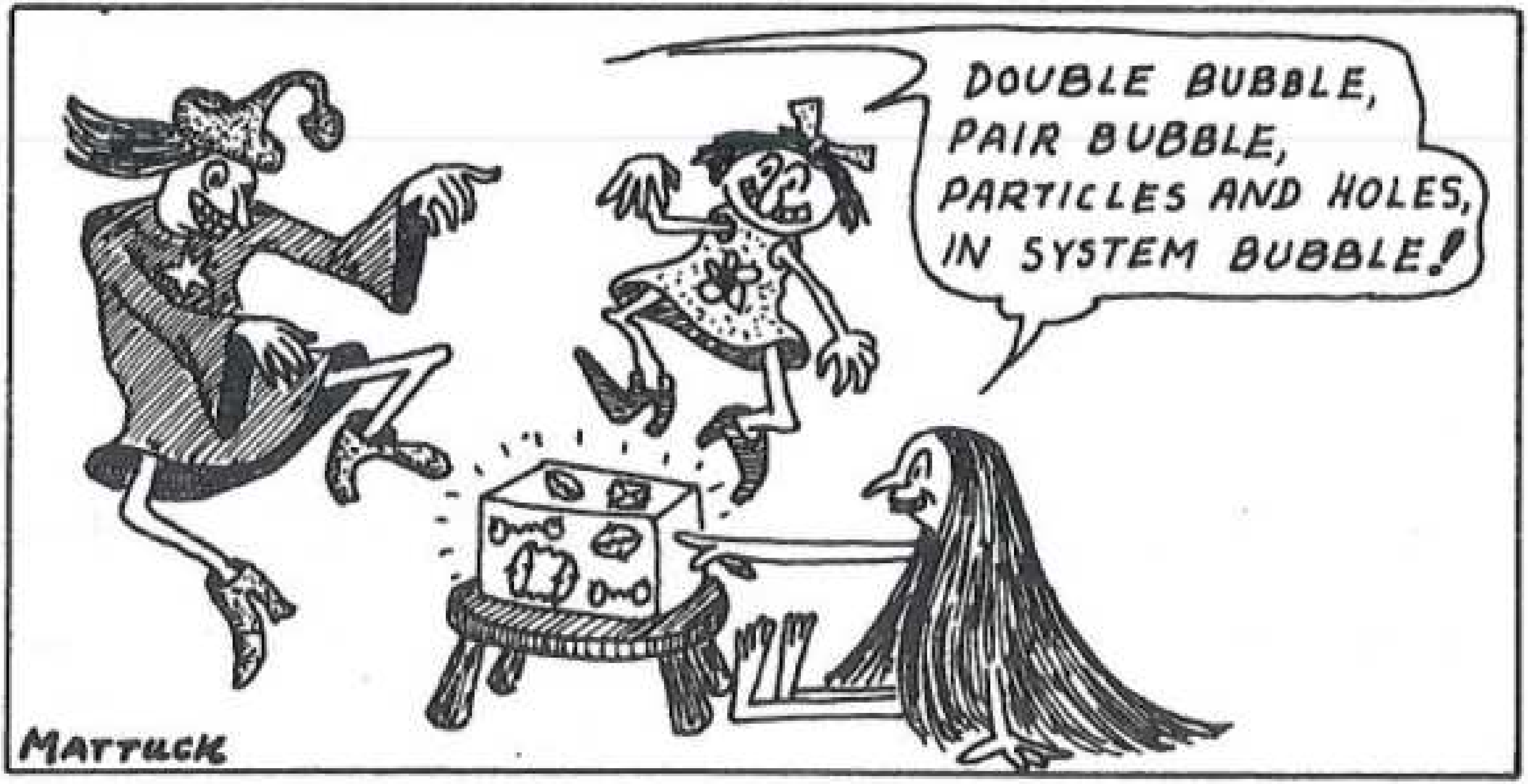


Fig. 1.5 *Modern View of a Many-body System in its Ground State*