Introduction to Particle Physics

LIP Summer Internships

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Particle Physics

Particle physics is a modern name for the centuries old effort to understand the basics laws of physics.

Edward Witten

Aims to answer the two following questions:

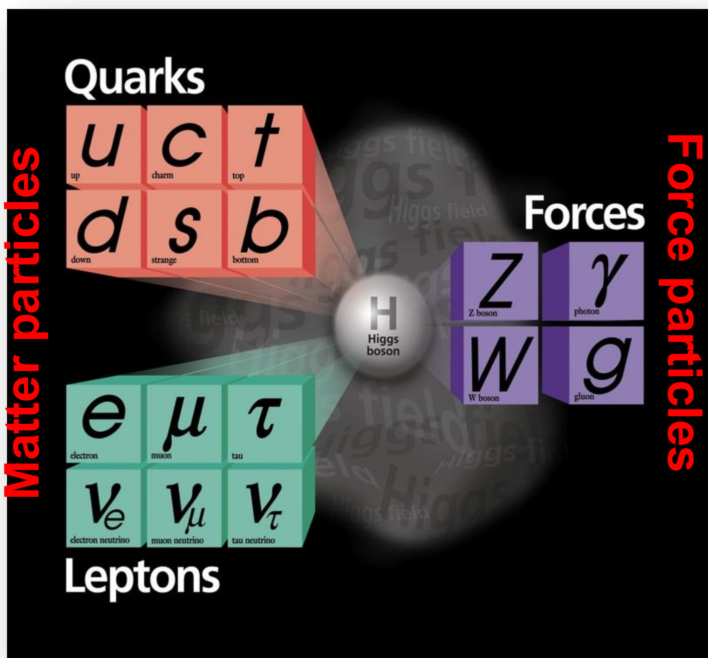
What are the elementary constituents of matter ?

What are the forces that determine their behavior?

The Standard Model

Over the last ~100 years: The combination of Quantum Field Theory and discovery of many particles has led to

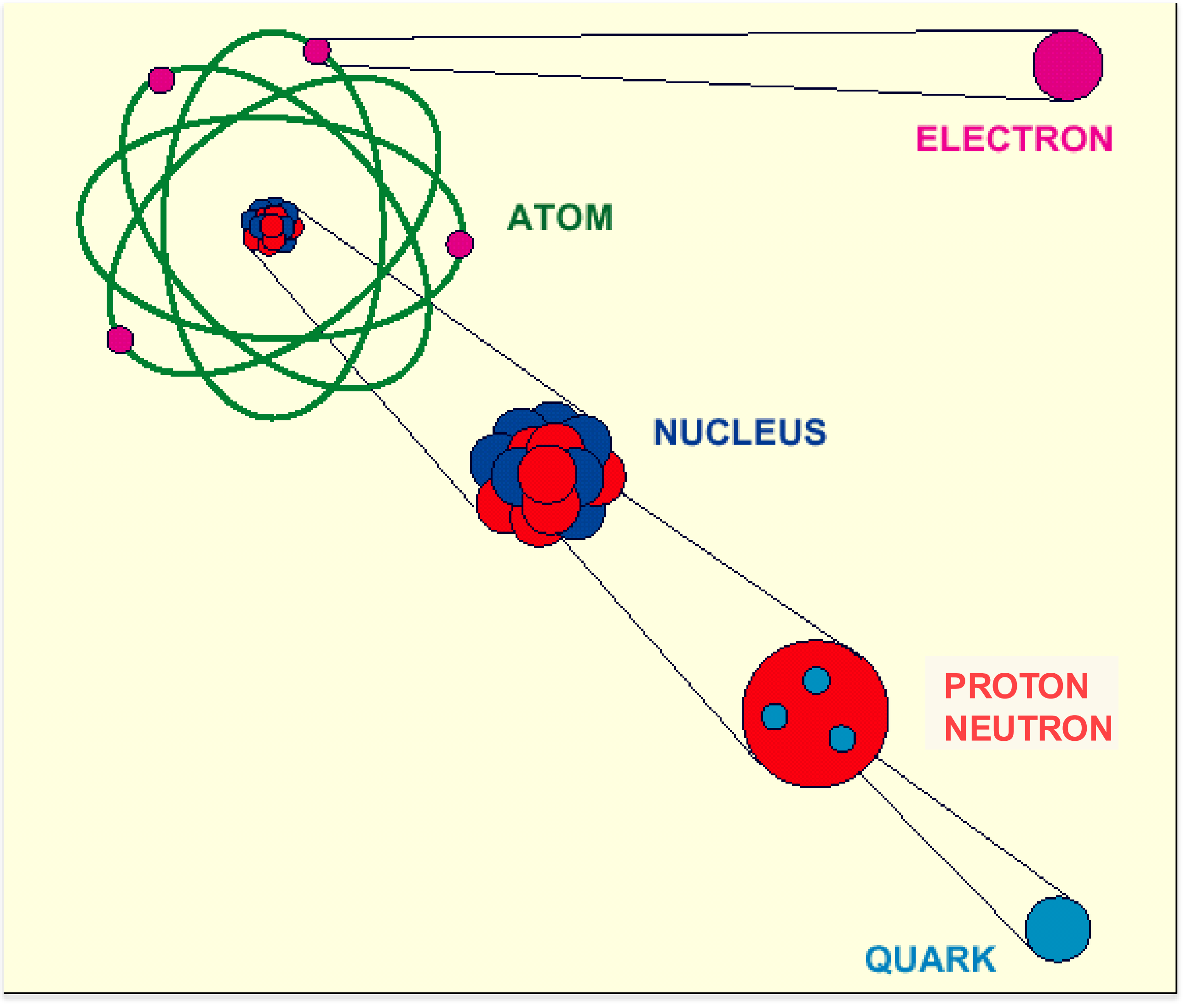
- The Standard Model of Particle Physics
  - With a new "Periodic Table" of fundamental elements



One of the greatest achievements of 20th Century Science

$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 + \frac{g^2}{4}(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu)(\lambda^2 + 2\lambda H + H^2) + \sum_{l,q,q'}(\frac{m_l}{\lambda}\bar{l}l + \frac{m_q}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q}'q')H$$

Constituents of matter



Forces: a history of unification

Apples fall to earth
Planets orbit sun
Moons orbit planets

Newton's Universal Law of Gravity

Electricity
Magnetism
Optics

Electromagnetism

Radioactive decays
Sun

Weak force

Electroweak Interaction

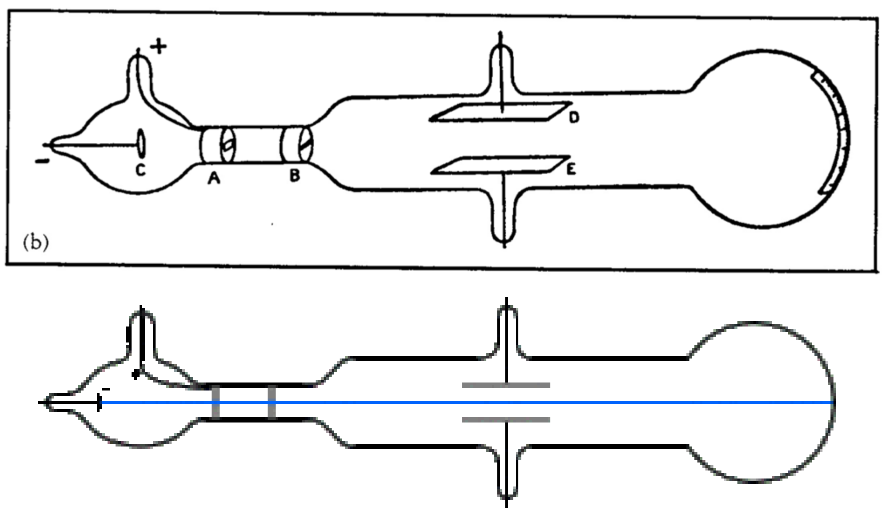
Atomic nucleus
Nuclear energy

Strong force

Electron, the first particle

In 1897 Thomson interprets the cathode rays in terms of a flow of electrons

Cathode ray tube used by Thomson



Vacuum inside the tube

Result: **e/m = 2.3 x 10^{17} esu/erg**

The Rutherford experiment

Experiment:

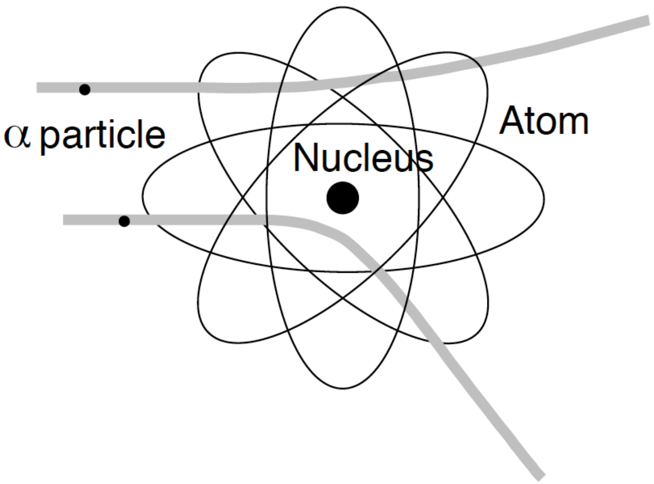
Alpha particles from the decay of polonium are sent on a very thin gold foil.

In some cases, deflections at wide-angle are observed, sometimes the particle is reflected back.

Ernest Rutherford
1871-1937

Awarded the Nobel Prize in 1908

A very dense nucleus concentrating all positive charges is responsible for the large deflections



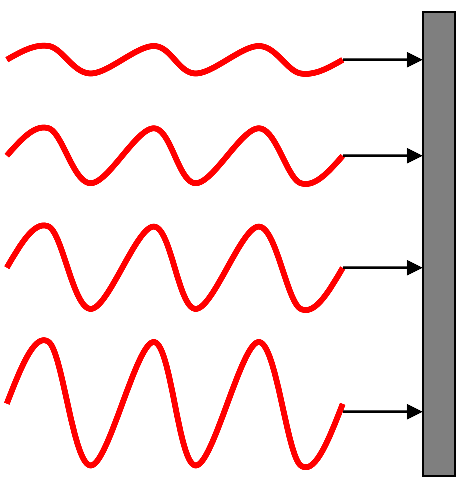
Photoelectric effect

Experimental observation:

Electrons are emitted from matter when light is incident

Increase energy of light by increasing amplitude

electrons emitted ?



No

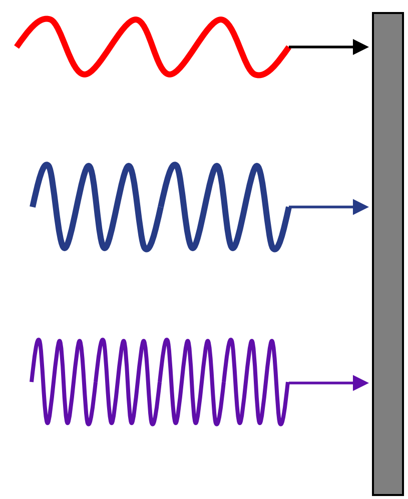
No

No

No

Vary light frequency at fixed amplitude

electrons emitted ?



No

Yes, electrons with low energy

Yes, electrons with high energy

No electrons are emitted until the frequency of the light exceeds a critical frequency

Einstein and the quantum of light

In 1905, Einstein proposed that the electromagnetic field is formed of quanta with $E=h\nu$. (ν = frequency of electromagnetic wave)

Later they were called photons.

Einstein's interpretation of the photoelectric effect:

- The impact of a photon is enough to extract an electron, if the photon energy exceeds the binding energy (W) of the electron in the atom.
- The electron is emitted with kinetic energy $E = h\nu\text{-}W$.

h - Plank constant ν - wave frequency

Particles and waves

In 1923, Louis de Broglie suggested that particles of matter, as the electron, have a dual nature - **particle and wave** - like electromagnetic radiation.

Louis de Broglie

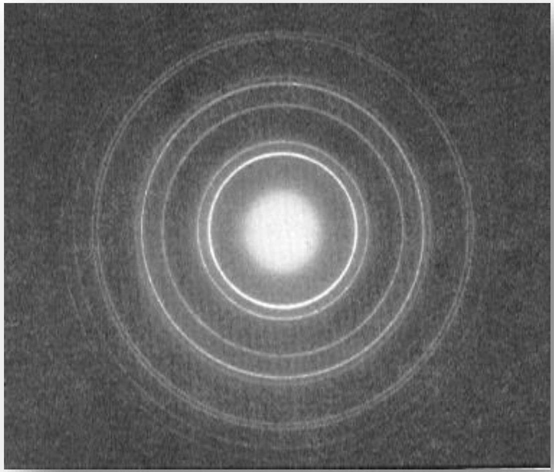
Particle **energy** in terms of wave **frequency**

$$E = h\nu$$

Particle **momentum** in terms of the **wavelength**

$$p = h/\lambda$$

These expressions are the main bridge between the two representations of reality.



Electron diffraction

Neils Bohr and the quantum atom

In 1913 Niels Bohr applies the idea of energy quantization to the atoms.

Bohr's postulates to explain the behavior of atoms:

a) the atomic electrons can only exist in certain orbits, known as quantum states;

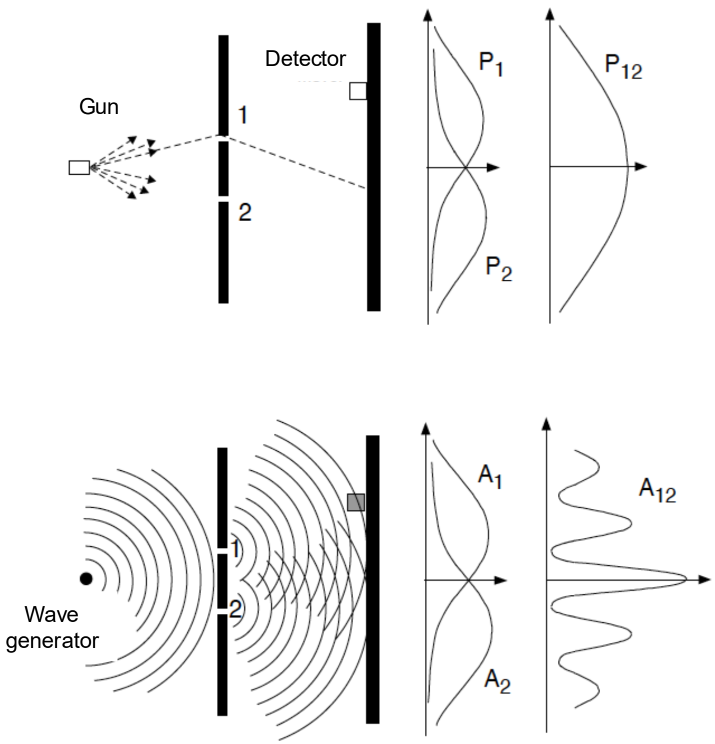
b) each quantum state corresponds a certain energy of the electron, and these energies can only take certain discrete values;

c) when in an excited state, the atom decays to the ground state emitting a photon of energy equal to the difference of the two states.

1885-1962

Awarded the Nobel Prize in 1922

Quantum physics is weird

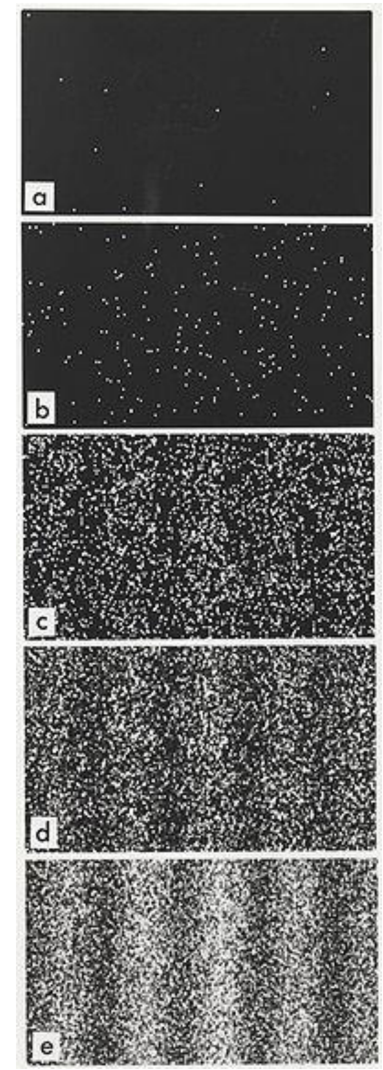


Shooting electrons into a screen with two slits

1. **Close one slit:** electrons behave as bullets

2. **Leave the two slits open:** electrons behave as waves

3. **Shoot electrons one-by-one with the two slits open:** the wavy pattern is still formed in the detector



Electron buildup over time

So, is it a particle or a wave?
It's still a mystery today.

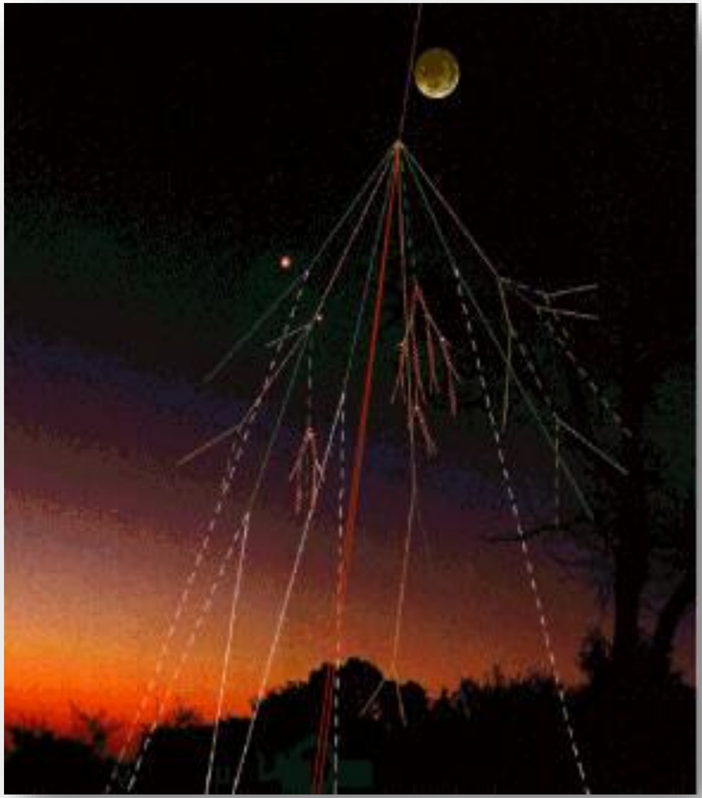
Quantum principles underlie the theories of atoms, nuclei and elementary particles developed in the 20th century.

Cosmic rays

Occasionally energetic particles from outer space enter our atmosphere and trigger a chain of particle interactions

New particles are created and then most of them decay

Source of many important discoveries in particle physics in 1930s-40s

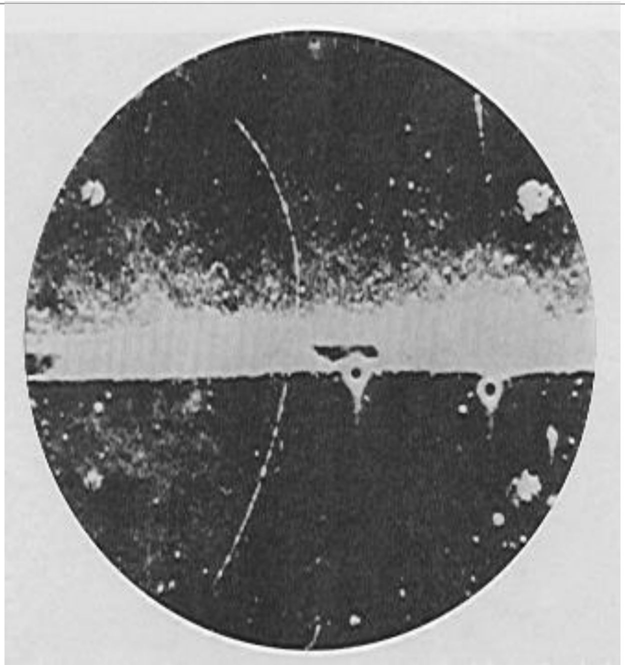


Discovery of antimatter

In 1932, Carl Anderson found particles with positive charge that could not be protons.

The new particle was the positron, the antiparticle of the electron.

Antiparticles were predicted by Paul Dirac in 1928 from relativistic theory of electrons



Positron photographed in a Cloud Chamber under a magnetic field.

Discovery of pion meson (π)

Prediction of pion existence — Yukawa 1935

- Nucleons (protons and neutrons) are held together by a force stronger than electrostatic repulsion of protons
- In 1935 Yukawa predicted existence of a mediator of the strong interactions.
- Short range of strong force led to estimation of its mass to be around 0.1 GeV.

Discovery of pions — Cecil Powell 1947

Detected in cosmic rays captured in photographic emulsion

Discovery of kaon meson (K)

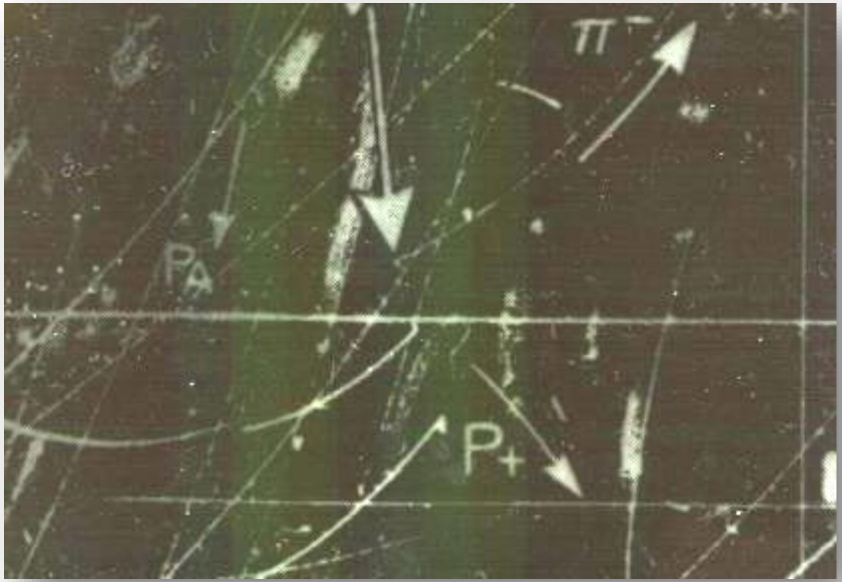
Discovery of strange meson (kaon)   Butler 1947

Cosmic ray particle with mass in between pion and proton mass.

(mass of K meson ~ 0.5 GeV)

Kaons were just like heavier pions.

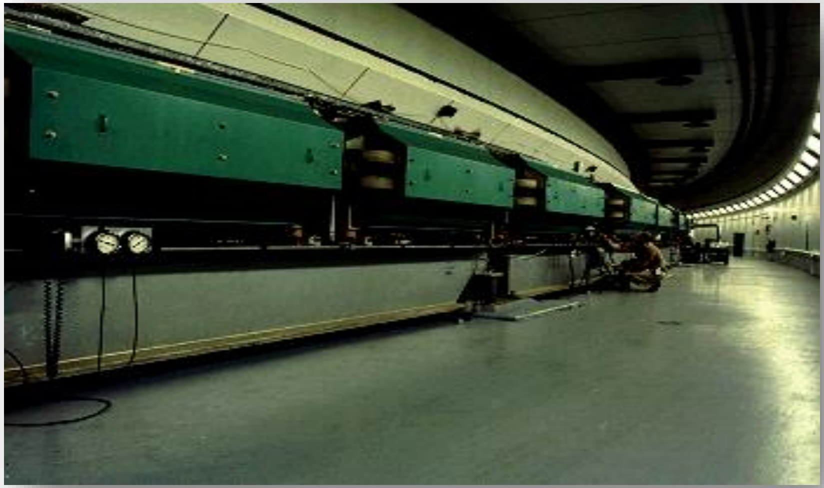
Kaons are always produced in pairs.



Particle accelerators

The rapid progress in particle accelerators allowed the **discovery of entire particle zoo** 1950's and 1960's

– e.g. Cosmotron at Brookhaven (first proton synchrotron 1952 - 2.3 GeV)

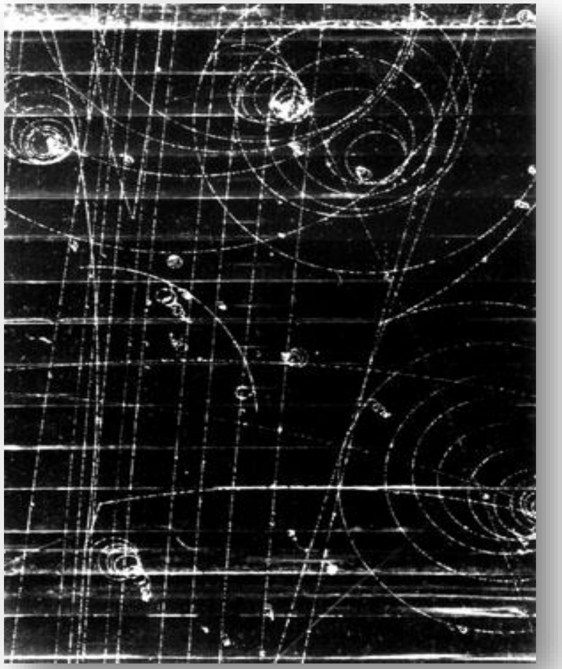


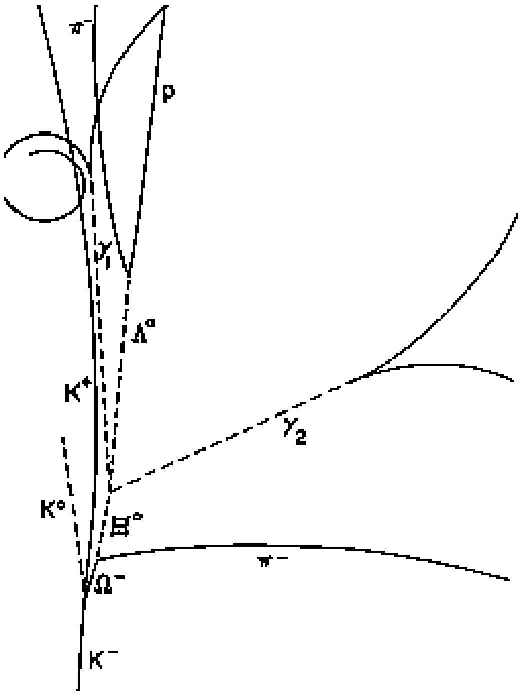
– Replaced by AGS in 1960's

Particle zoo

- New particles either pion-like (mesons) or proton-like (baryons)
- Either type can be strange or non-strange.
- Mesons and baryons (i.e. hadrons) feel strong interactions contrary to leptons (like electrons and muons)
- Example: discovery of strange baryon Ω^- (omega minus)

Bubble chamber





Quarks! up, down, strange…

A SCHEMATIC MODEL OF BARYONS AND MESONS

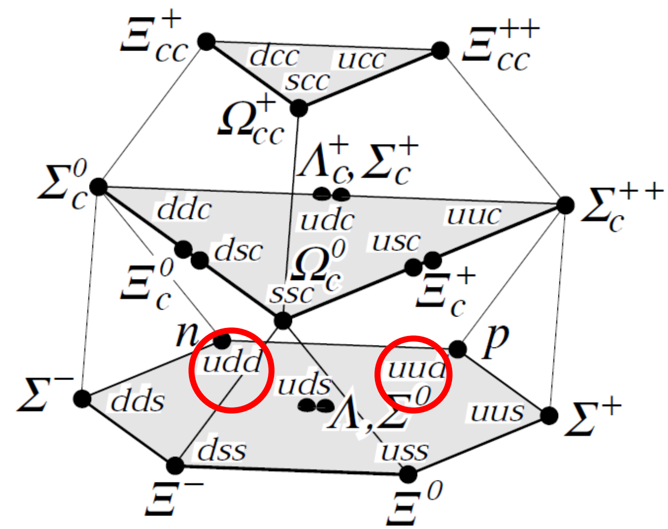
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6)

6) James Joyce, Finnegan's Wake (Viking Press, New York, 1939) p.383.

Gell-Man, Zweig 1964



- Mesons are composed of quark-antiquark
- Baryons are composed of three quarks

Electrical charge:

u = +2/3

d = -1/3

proton = uud

neutron = udd

Quark model of hadrons

up (u)	charm (c)	top (t)
down (d)	strange (s)	bottom (b)

In each generation there is a quark doublet

- The upper member has charge + 2/3
- The lower member has charge -1/3

Mesons are composed of quark-antiquark pair

Baryons are composed of three quarks

Quarks and gluons in the proton

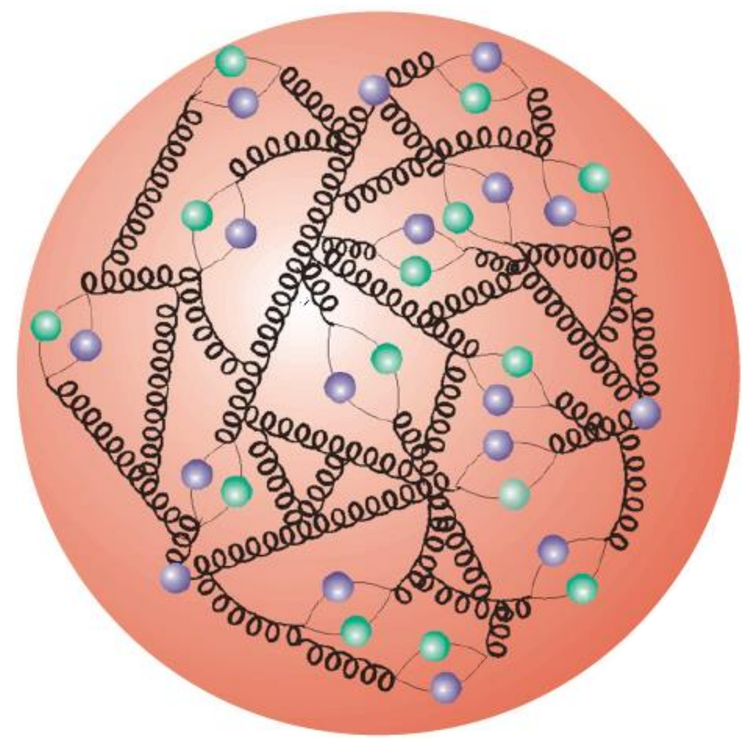
Quark model was confirmed experimentally in 1968 by a Rutherford-type experiment at SLAC (Friedman, Kendall, Taylor)

Shooting 20 GeV electrons into protons allowed the investigation of distances of the order of 10^{-18} m.

The results of the experiment are compatible with the diffusion of electrons by point particles existing inside the hadrons!

A theory of quark interactions was developed later: **quantum chromodynamics (QCD)**

Gluons mediate the strong forces



Picture of the proton today

Quantum Chromodynamics

Quantum Chromodynamics (QCD) is the quantum theory of strong interactions

No free quark has ever been observed.

The strength of the strong interaction grows with distance:

- The binding energy can, at some point, become matter giving rise to new quark-antiquark pairs.
- These combine with initial quarks to create other hadrons.

Back in time to the 30’s:

neutrinos and the birth of the Weak Interaction

Neutrinos

Apparently in the β **decay** the energy is not conserved:

- A nucleus A emits an electron and becomes a nucleus B *($A \rightarrow B + e^-$)*
- The energy of the electron should be always the same

Experimental data:

In the decay of tritium ($^3H_1$) to the helium ($^3He_2$) the electrons have energies that are distributed between zero and 17 keV

Pauli suggested that another neutral particle is emitted, which is not detected in experiments:

$$A \rightarrow B + e^- + \nu$$

The new particle was called neutrino (ν).

Weak interaction

In 1933 E. Fermi proposed a theory of beta decay:

the emission of the electron and the neutrino is the result of the transformation of a neutron into a proton in the nucleus

$$n \rightarrow p + e^{-} + \nu$$

Fermi understood that a **new force** is involved in the beta decay.

The long lifetime of beta decay means that the force has a very small intensity.

For this reason, the new force was named **weak interaction.**

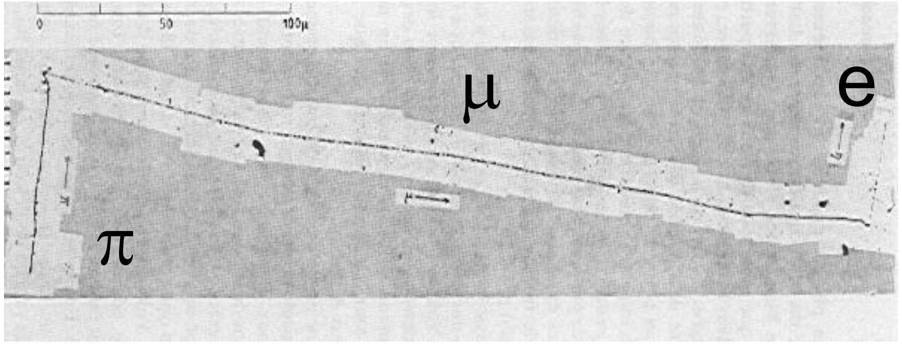
Enrico Fermi

The discovery of the muon

Events in cloud chambers with the trace of a particle crossing significant thicknesses of matter without interaction.

Neddermeyer and Anderson (1936) concluded that these penetrating particles could not be protons, electrons or positrons, but particles with mass of the order of 100 MeV:

it was the muon (μ)



pion decays to muon, followed by muon decay to electron and neutrinos

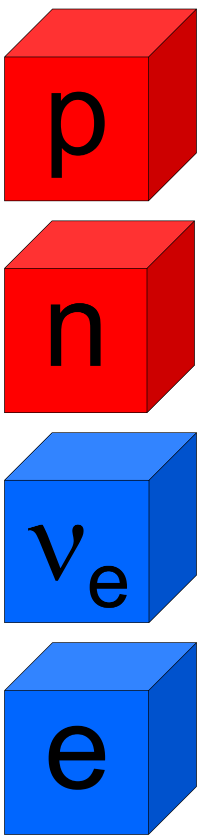
$$\mu^- \rightarrow \nu_\mu \, e^- \, \nu_e$$

What is the place of the muon in the structure of matter?

The smallest building blocks of matter?

Before muon discovery

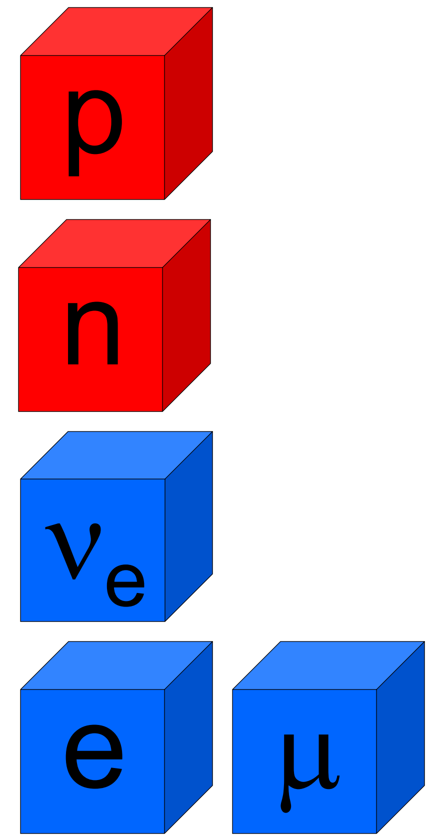
After muon discovery



In 1936, the vision of the building blocks of matter was seriously challenged

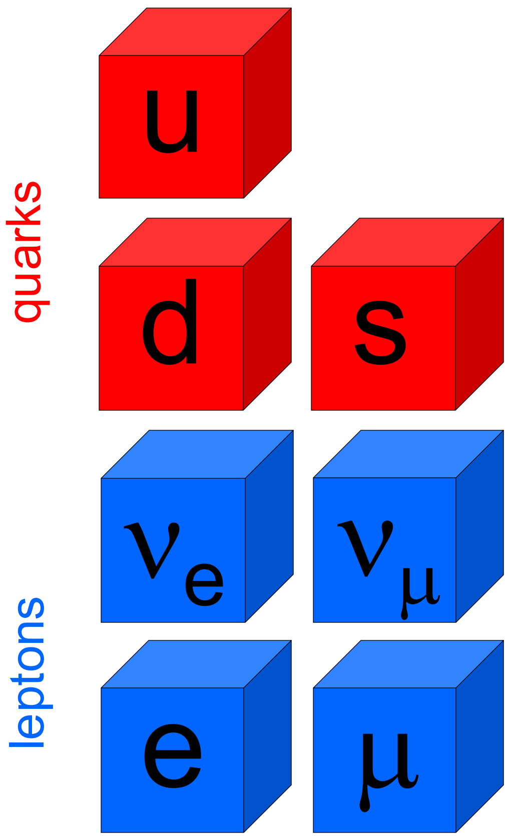
It was the first evidence of the mystery of the particle generations

90 years later the mystery is still with us



The smallest building blocks of matter?

In 1964 the quark model changed the table:

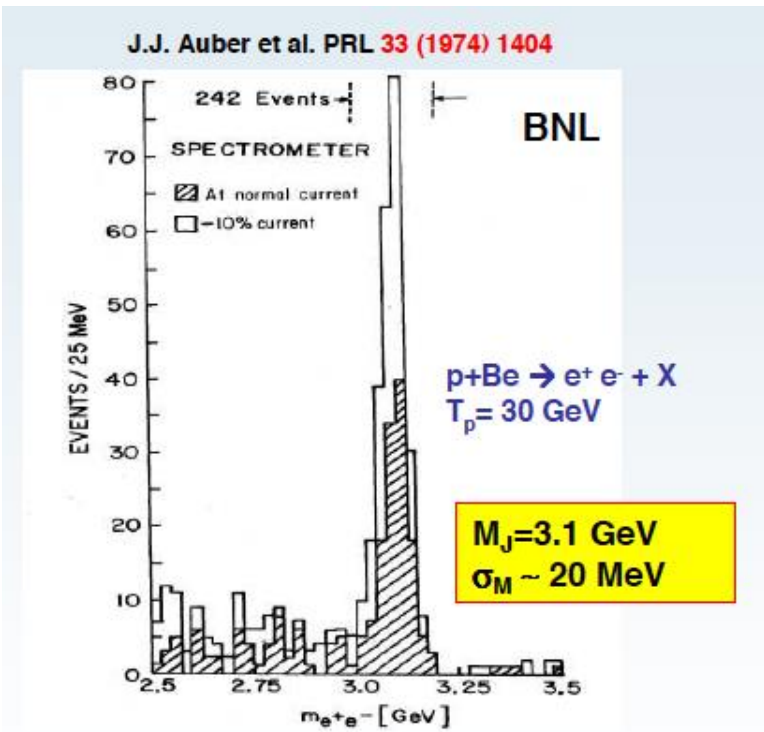


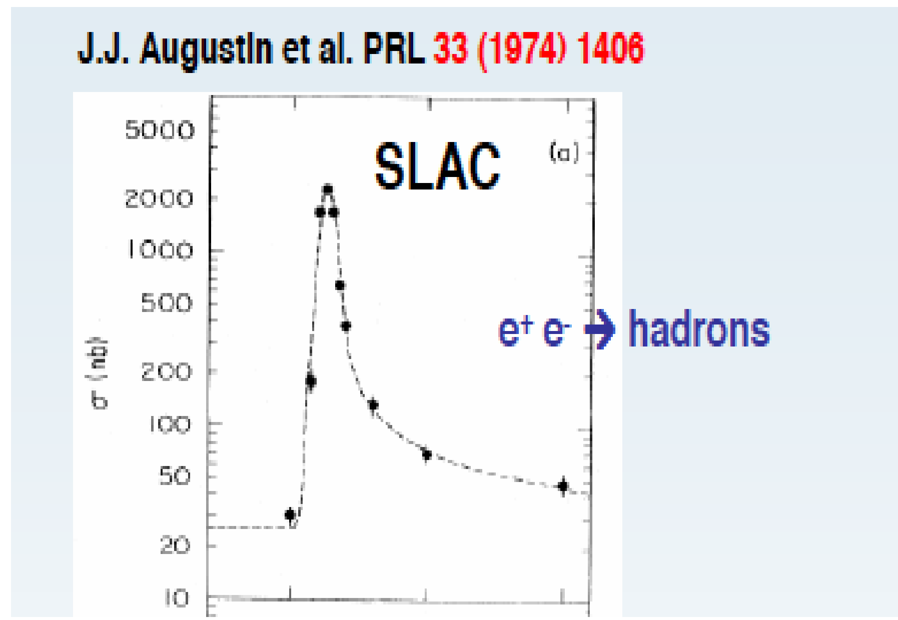
Is one piece missing?

Charm quark discovery

J/Ψ discovery – the 1974 "November Revolution"

The new particle is composed of charm and anti-charm



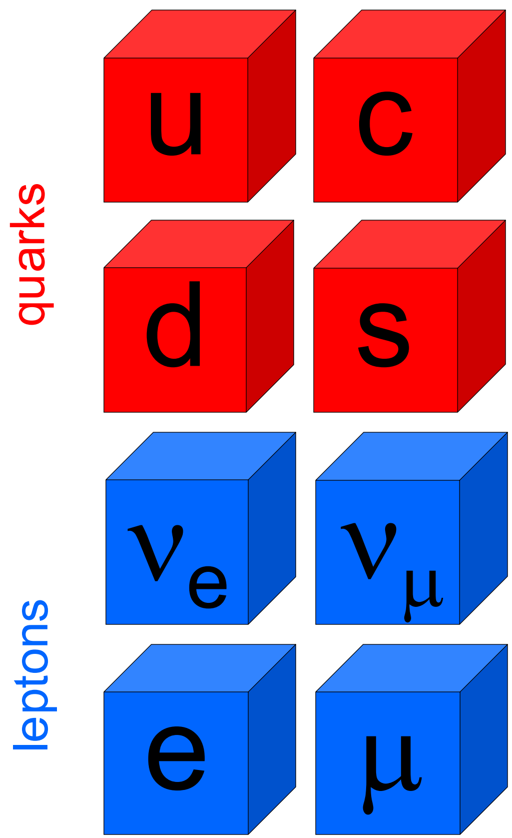


Proton beam at AGS, Brookaven

Electron-positron collider SPEAR, SLAC, Stanford

The smallest building blocks of matter?

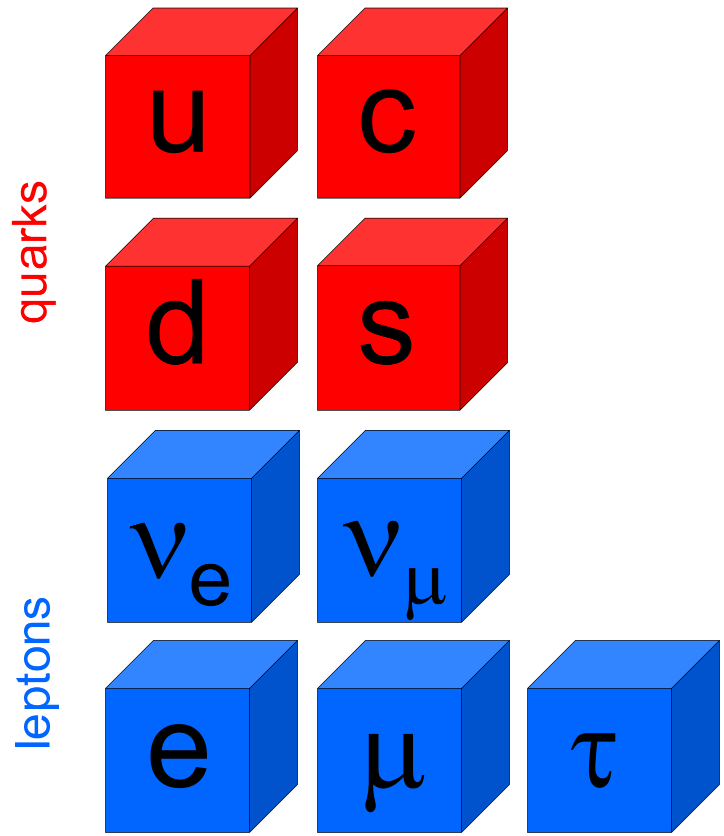
… and it became



A nice complete set, until a discovery in 1977 made the table look like…

The smallest building blocks of matter?

…this:



Again a whole missing column?

Third lepton and quark generation

- Discovery of **tau lepton** Perl 1975-77
  - $m_\tau \sim 1.8$ GeV
- Discovery of **bottom quark** Lederman 1977
  - $m_b \sim 4.7$ GeV
- Discovery of **top quark** Fermilab 1995
  - $m_t \sim 173$ GeV

Bottom and top quarks in the third generation are called heavy flavors

Neutrino species

Neutrinos have a very small interaction probability:

a neutrino has only a chance over 10 millions to interact when crossing the whole Earth.

In 1955 F.Reiner and C.Cowan detected for the first time interactions of neutrinos with matter, using the huge neutrino flux (10^{13}/second/cm^2) from the nuclear reactor Savannah River:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

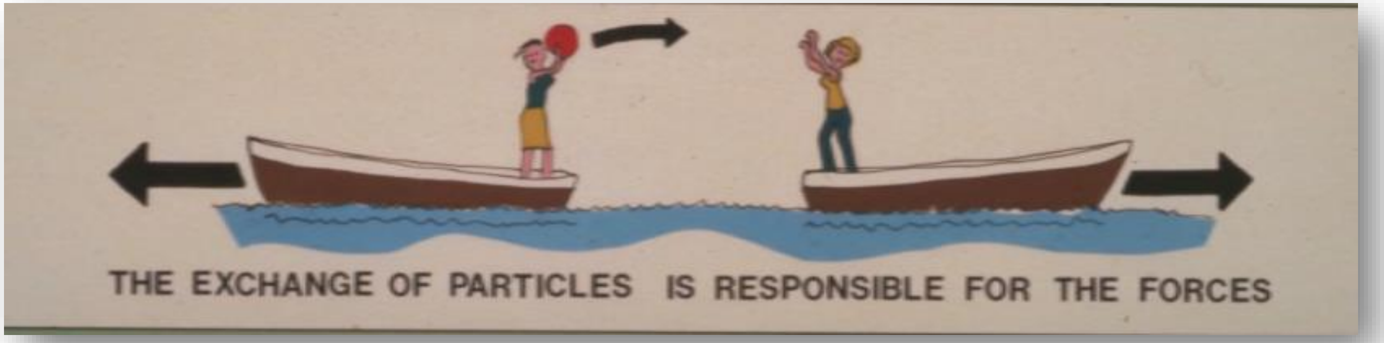
In 1962 Lederman, Schwartz and Steinberger found the muonic neutrino using neutrinos from the π decay:

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

Clyde Cowan conducting the neutrino experiment 1956

Force fields and intermediate particles

In quantum field theory the electromagnetic interaction between two charged particles is due to the exchange of "virtual photons" between the particles.

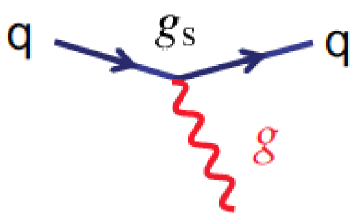


The quantum theory does not invalidate the classical theory, but restricts its scope:

When the number of photons exchanged is large, the classical field description is valid.

Standard model interactions

STRONG

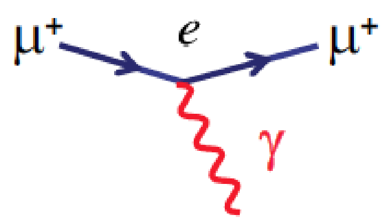


Only quarks

Never changes flavour

$\alpha_S \sim 1$

EM

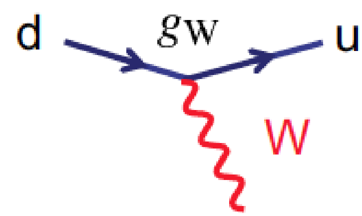


All charged fermions

Never changes flavour

$\alpha \simeq 1/137$

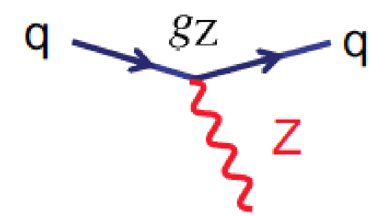
WEAK CC



All fermions

<u>Always</u> changes flavour

WEAK NC



All fermions

Never changes flavour

$\alpha_{W/Z} \sim 1/40$

Gluons
massless

Photon
massless

W+, W-
very massive

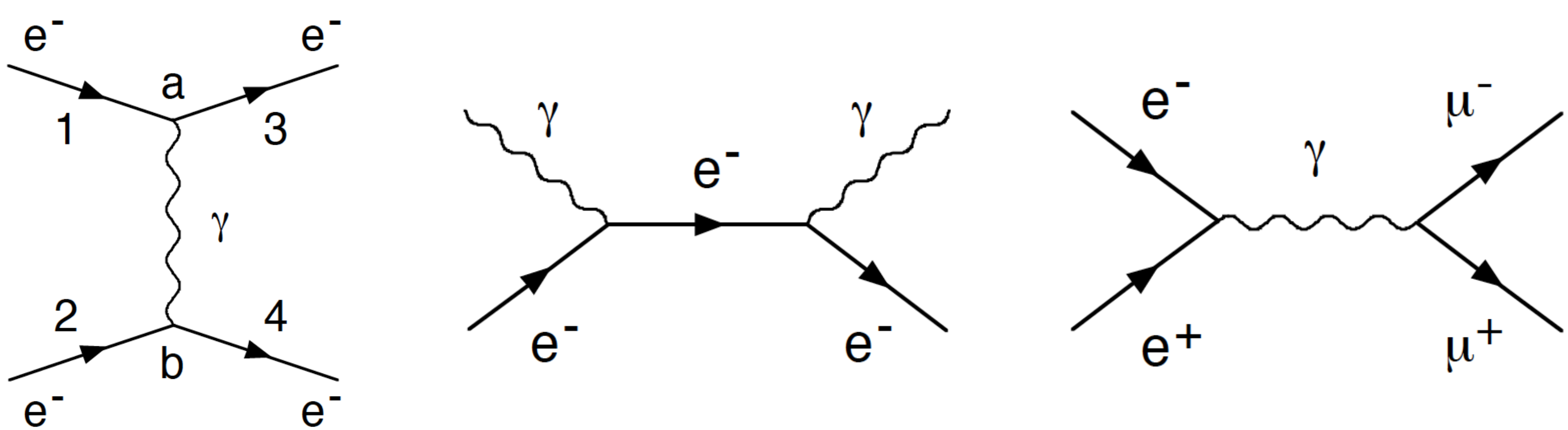
Z^0
very massive

Intermediate particles are called Gauge Bosons

Feynman diagrams

Quantum theory of the electromagnetic interaction, initiated by Dirac in 1927, required more than twenty years to reach the final formulation.

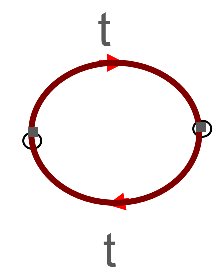
In the fifties, Richard Feynman introduced the **Feynman diagrams** which are pictorial representations of the mathematical expressions governing the behavior of particles interactions.



Quantum field theory

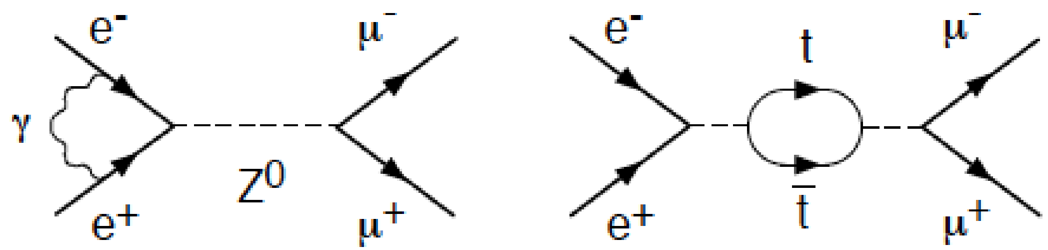
A particle-antiparticle pair can pop out of empty space ("the vacuum") and then vanish back into it

These are *Virtual* particles.



Vacuum Fluctuation
Involving top quarks

Examples of Virtual particles:



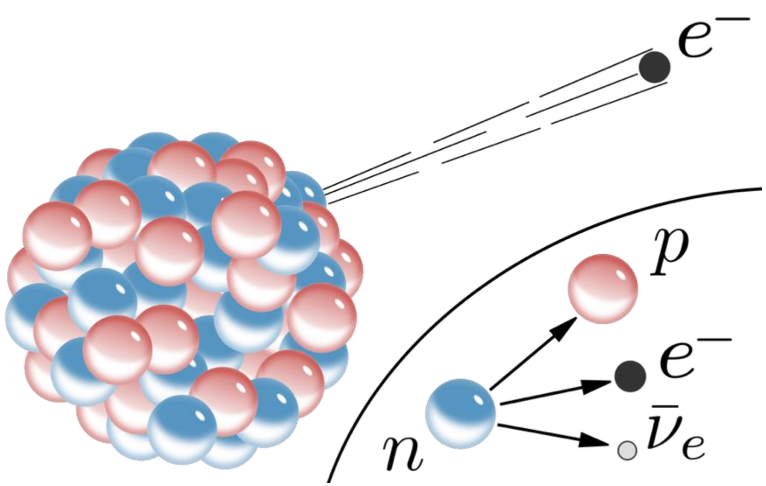
This has far-reaching consequences

The structure of the universe depends on particles that ***don't exist in the usual sense***

Beta decay revisited

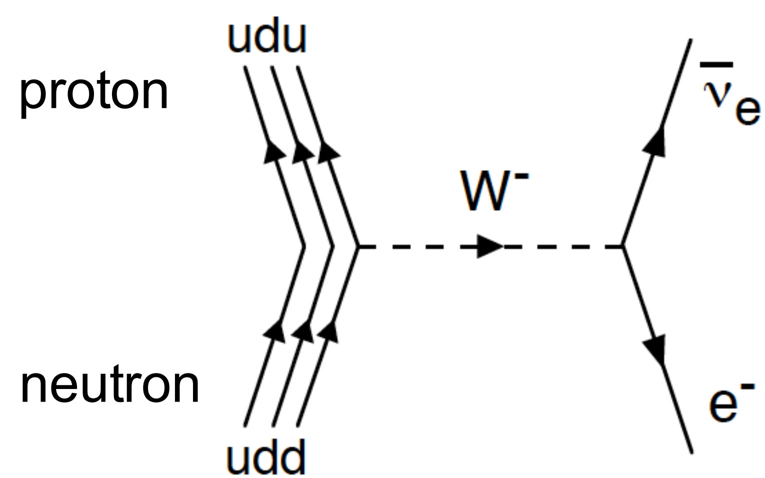
Fermi theory (1930-35):

the neuron decays in a proton, electron and neutrino



Standard Model (1960-65):

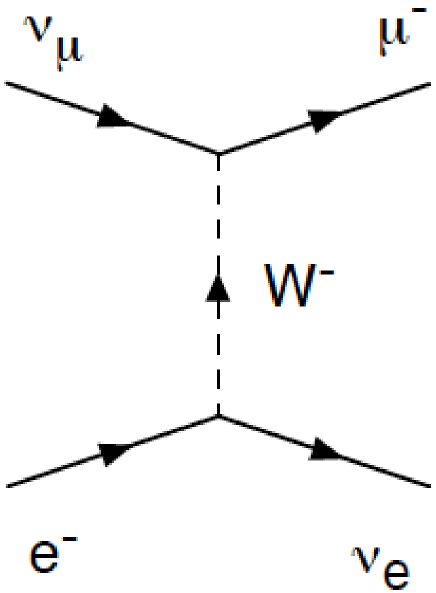
a quark d in the neutron emits a W$^-$ and is transformed into a u quark; the W$^-$ decays in a electron and a anti-neutrino



Neutrino interactions

Muonic neutrino beam interacts with atomic electrons (or with quarks) in the target.

The outgoing muon provides a clean signature of the process



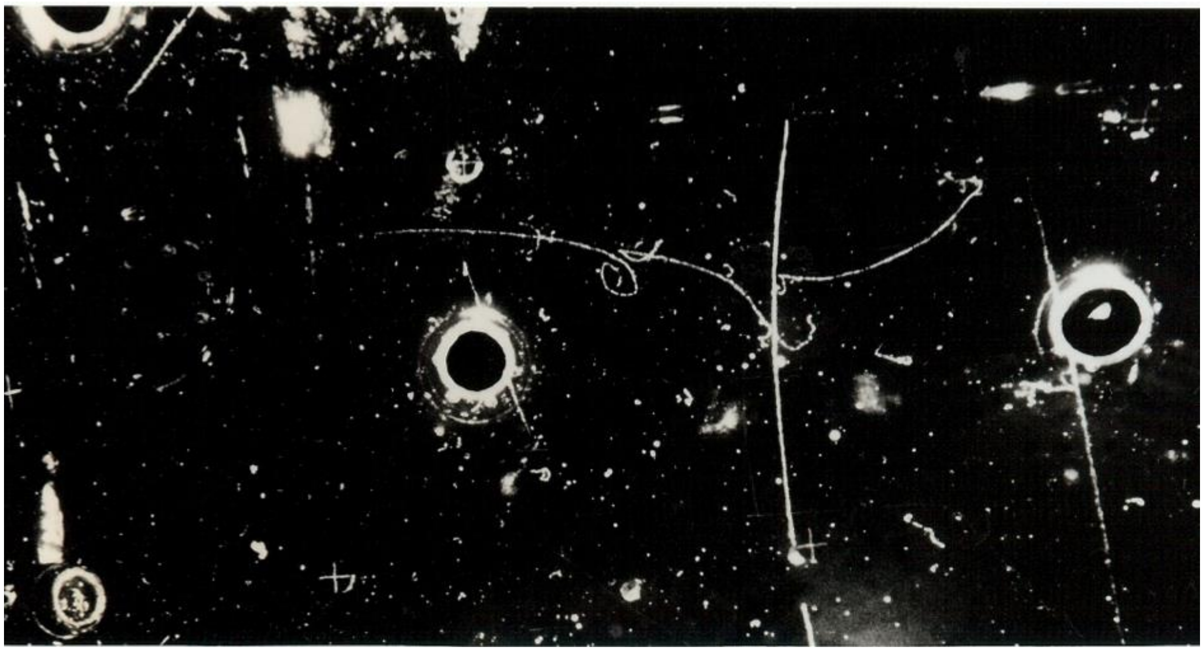
"Charged current" neutrino interaction

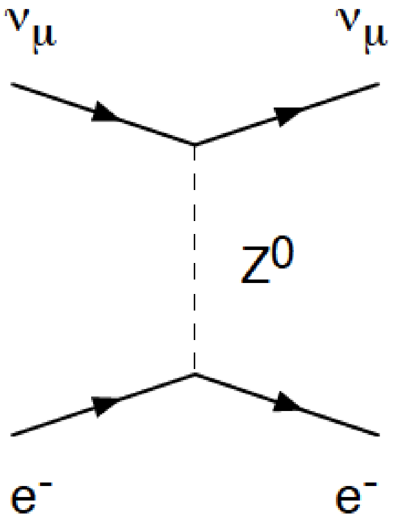
W boson is exchanged

Discovery of neutral currents

In 1973 at CERN, **neutral currents in weak interactions** were discovered. It was a crucial discovery.

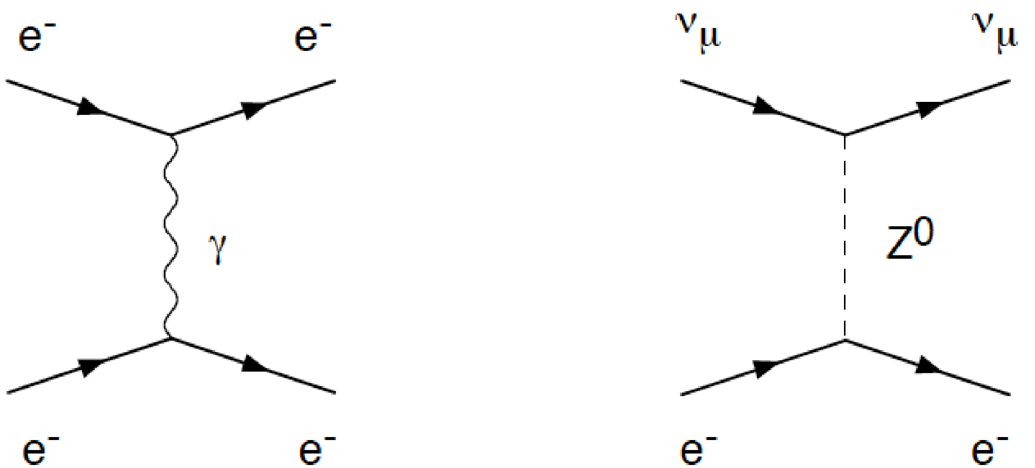
First observation of events $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$





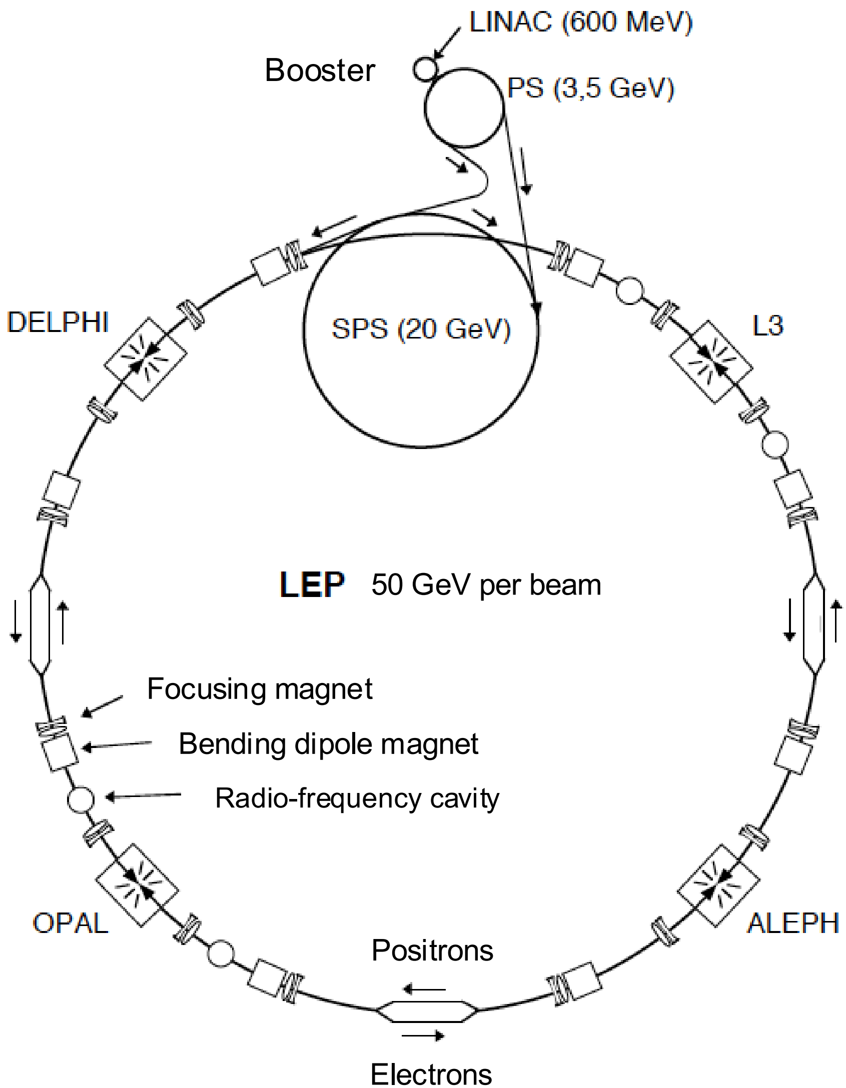
Weinberg-Salam model

In 1967-68 Weinberg and Salam proposed a theoretical model with a **unified description of the electromagnetic and weak interactions.**



The “weak force” is weak because the probability to exchange a massive particle, the Z^0, is much less than the probability of exchanging an object of zero mass as the photon

Colliders



Colliding beams:
the path to higher energy

Energy available to produce heavy particles is the Center of Mass Energy (E_{CM})

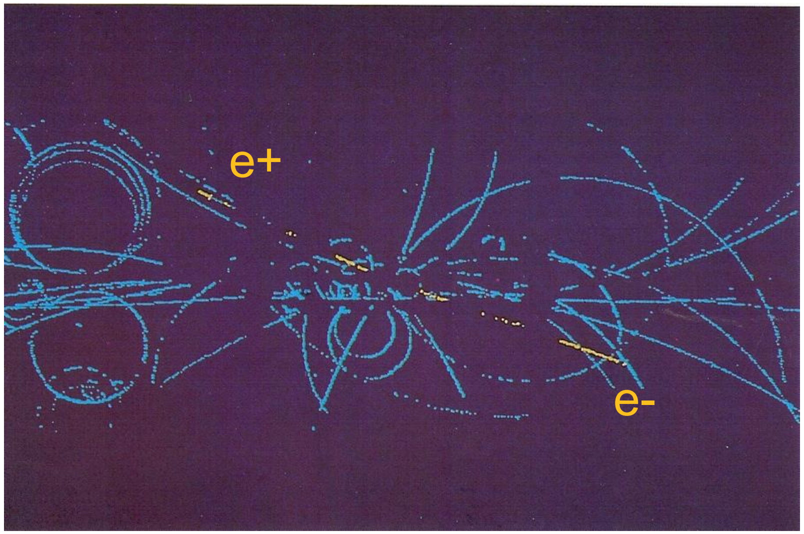
- Beam-Target:
  $\sqrt{s} = E_{CM} = \sqrt{2.E_{beam}.m}$
- Beam-Beam:
  $\sqrt{s} = E_{CM} = 2.E_{beam}$

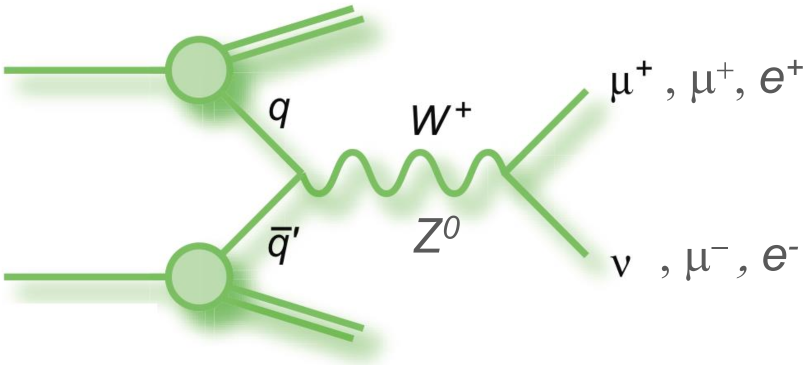
Discovery of W and Z bosons

Based on available experimental data, the Standard Model predicted the mass of the W and Z bosons to be around 80 and 90 GeV.

C. Rubbia proposed the transformation of Super Proton Synchrotron (SPS) at CERN in a **proton-antiproton collider** (energy 540 GeV)

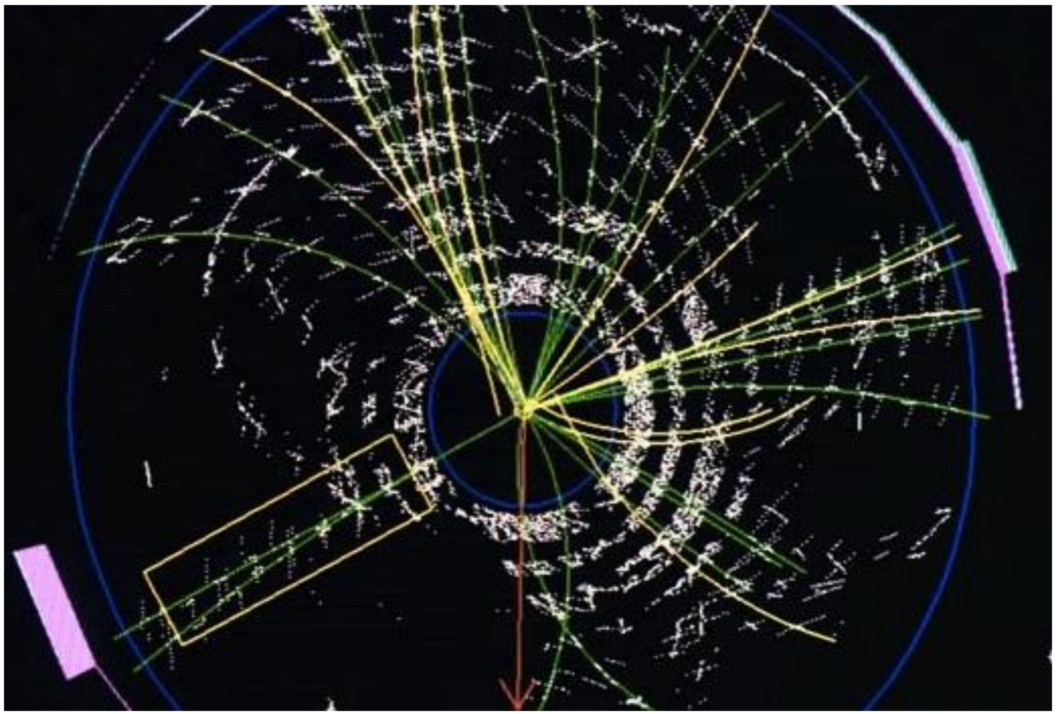
In 1983 the experiments UA1 and UA2 observed the W and Z bosons

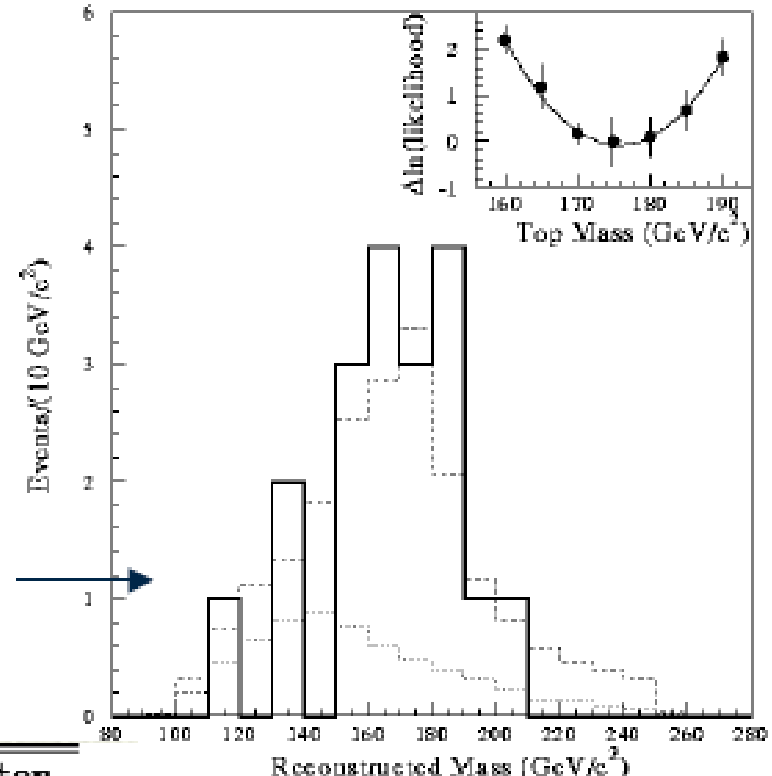




Top quark discovery

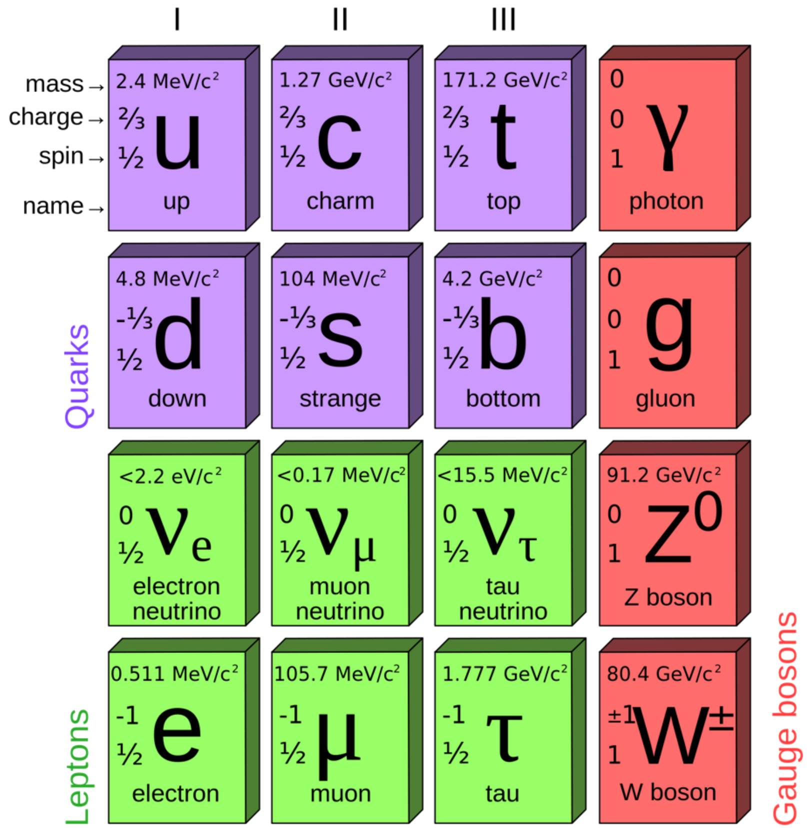
Top quarks were seen for the first time in 1995 at Fermilab near Chicago

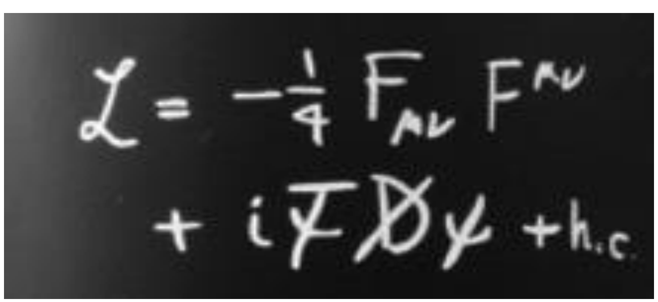




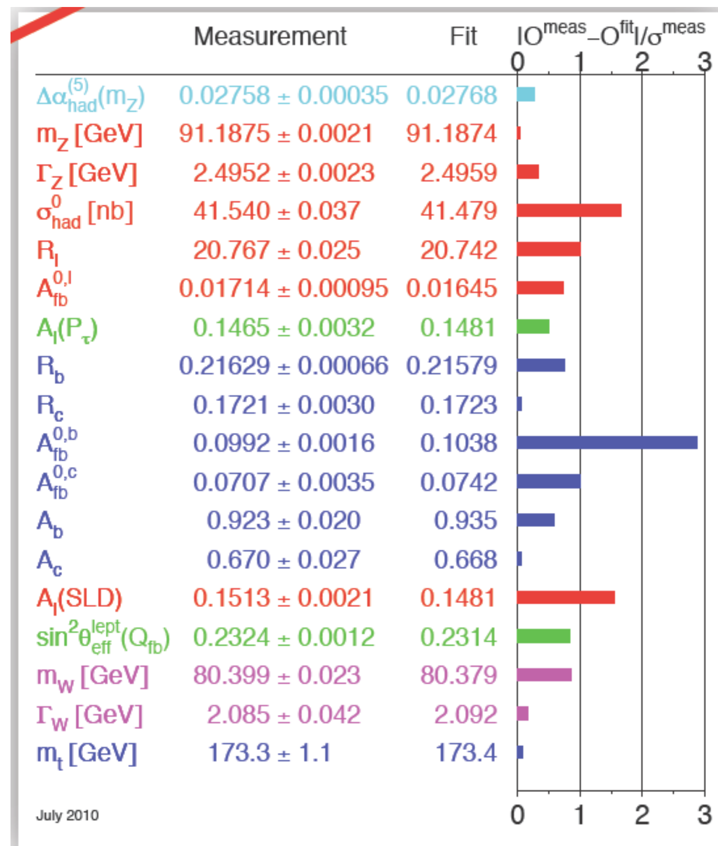
Channel:	SVX	SLT	Dilepton
observed	27 tags	23 tags	6 events
expected background	6.7 ± 2.1	15.4 ± 2.0	1.3 ± 0.3
background probability	2×10^{-5}	6×10^{-2}	3×10^{-3}

Putting all together





STANDARD MODEL OF ELEMENTARY PARTICLES



Confirmed at sub 1% level!

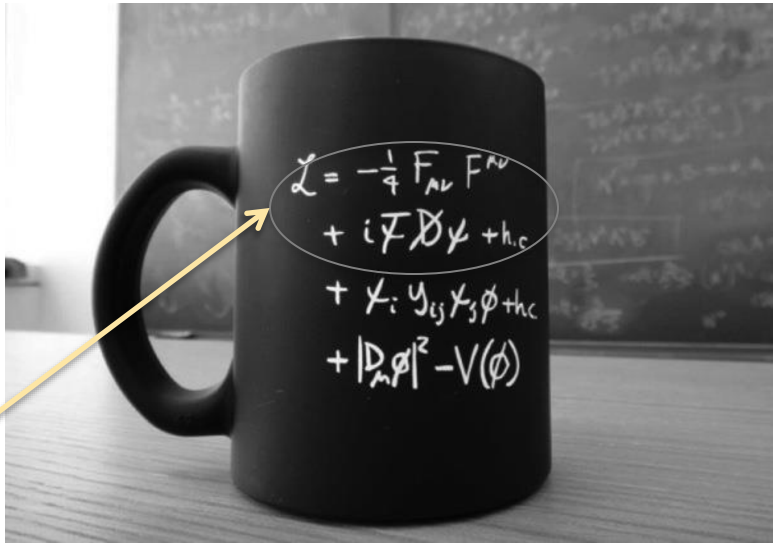
What's missing?

The equations only made sense if all the gauge bosons, and all the quarks and leptons, had no mass and moved at the speed of light!

Electroweak unification

Electromagnetic and **weak forces** have the same origin

The **electroweak theory** is based in an **underlying symmetry** between the two interactions



The equations of this theory imply that **all particles have zero mass**

BUT:

Electromagnetic interaction:

Photon **m=0**

Weak interaction:

Bosões W e Z **m~80-90 GeV**

Different masses of γ, W and Z **breaks the symmetry**

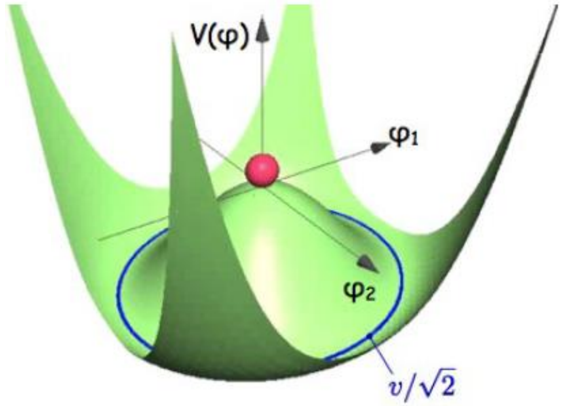
The Higgs exists in the vacuum

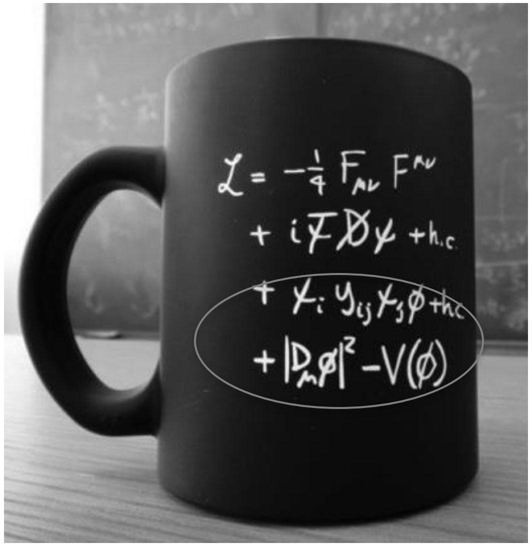
Key postulate of the "Higgs mechanism":

A new force field, the Higgs field, has an ***average value in the vacuum*** that became non-zero as the early universe cooled.

The Higgs mechanism

Spontaneous symmetry breaking





Higgs field:

- The Higgs field fills the space of the whole Universe
- The field has a non-zero value in the energy minimum
- Symmetry is broken when the field is at a minimum
- W and Z particles get mass through the interaction with the Higgs field

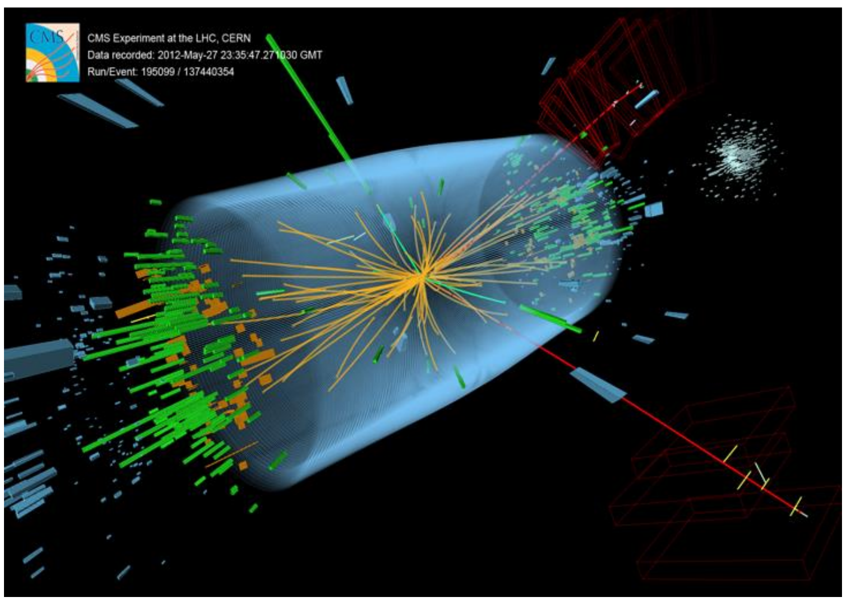
The Terascale and the LHC

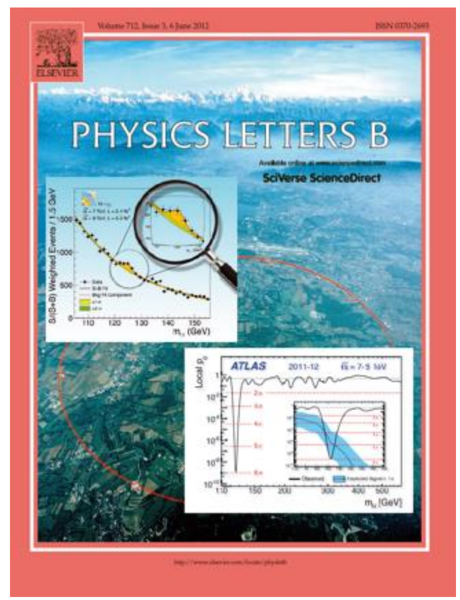
The Standard Model would fail at high energy without the Higgs boson or other 'new physics'.

It was expected that the 'new physics' would manifest at an energy around 1 TeV accessible at the LHC for the first time.

Higgs boson discovery in 2012

- **A major discovery in physics**
- **A new paradigm:** the space in the whole Universe is filled with the Higgs field
- **The study of the nature and properties of the Higgs boson is a scientific imperative for the next decades**





End of lecture