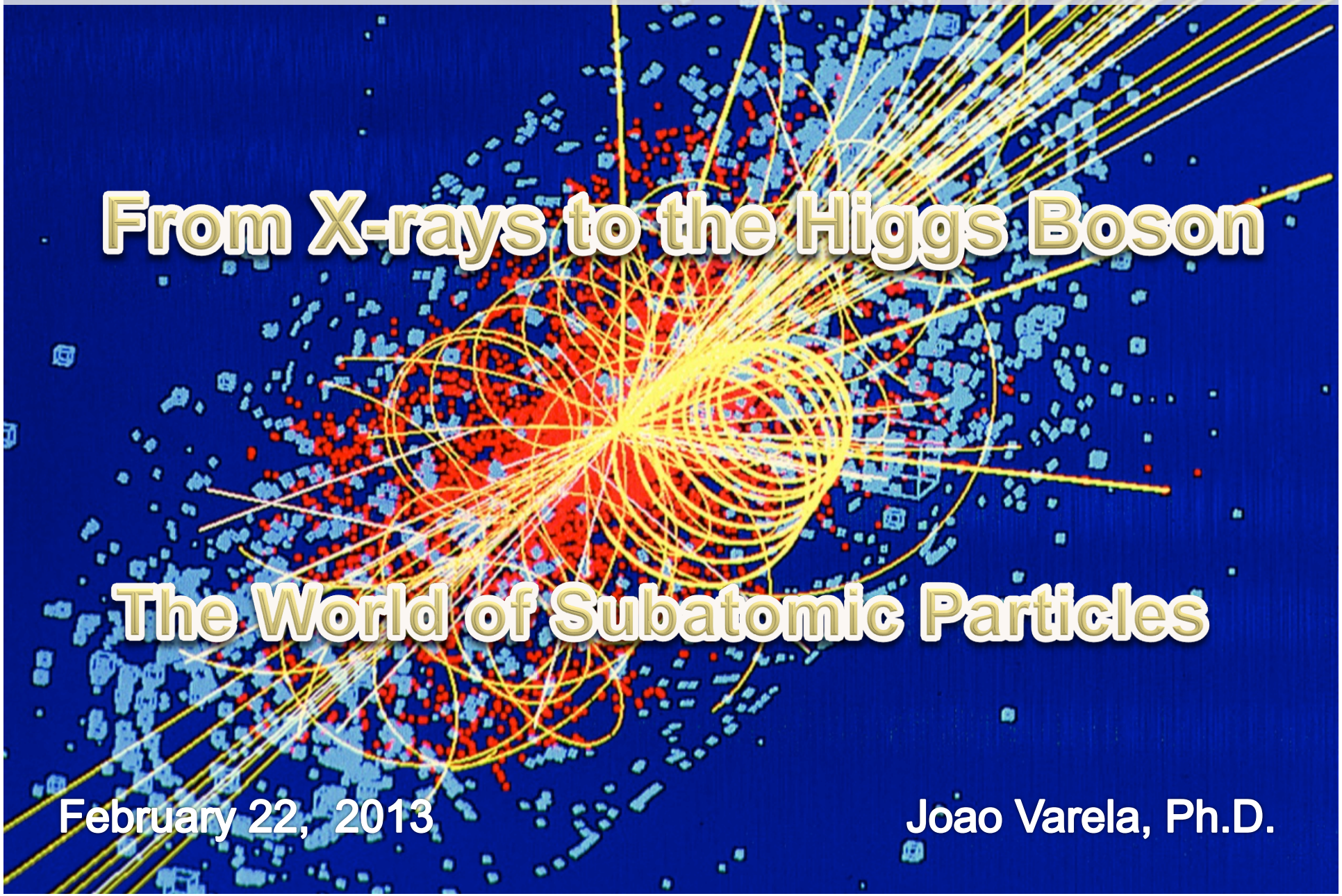
SCIENTIFIC AMERICAN Travel BRIGHT HORIZONS 16



From X-rays to the Higgs Boson

The World of Subatomic Particles

February 22, 2013

Joao Varela, Ph.D.

Lectures on the Higgs Boson

Lecture 1:

From X-rays to the Higgs Boson

The World of Subatomic Particles

Lecture 2:

The Big Bang Factory

Story of the World's Largest Machine

Lecture 3:

The Higgs Boson and You

Why Society Should Invest in Big Science

Lecture 4:

The Higgs Boson

What Is It and How Was It Discovered?

Lecture 5:

Beyond the Higgs Boson

Open questions in particle physics

From X-rays to the Higgs Boson

The World of Subatomic Particles

The objective of this lecture is to (re)discover the Standard Model of Particle Physics

Plan:

- The atom
- The quantum revolution
- Two new interactions
- A particle zoo
- New order: the standard model
- What's missing?

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:

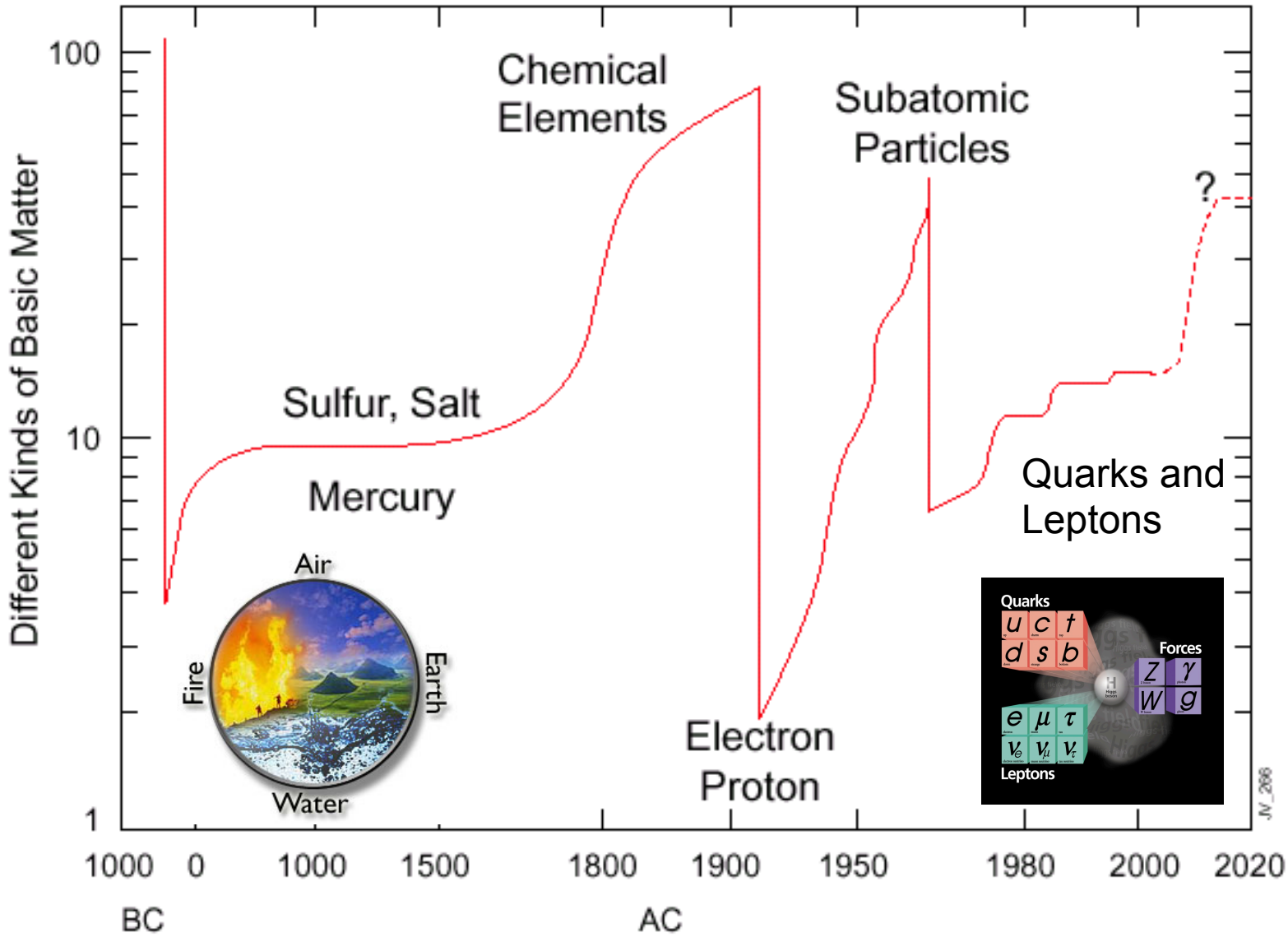
What are the elementary constituents of matter ?

What are the forces that determine their behavior?

Experimentally

Get particles to interact and study what happens

Constituents of matter along History



The periodic table of the elements

By the end of the 19th century, scientists had characterized many “elements”, *indivisible* in chemical reactions, leading to the modern “periodic table”:

Group → / Period ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 UUb	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

“Periodic”: elements in same column have similar chemistry.

The periodic table of the elements

Group → / Period ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	
4	19 K	20 Ca		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn			33 As	34 Se	35 Br	
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	

Dmitri Mendeleev wrote an early version in 1869.

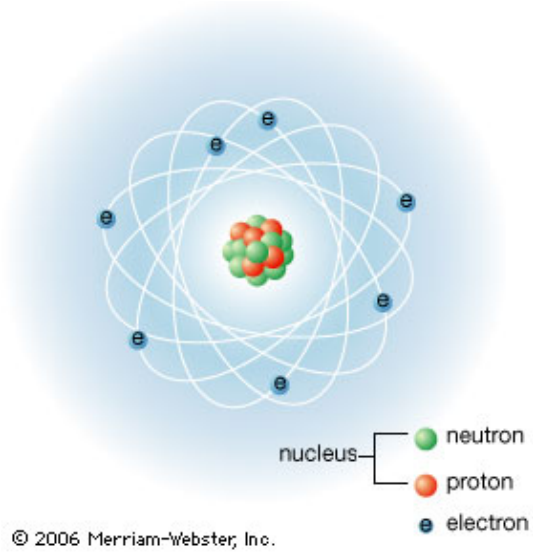
Mendeleev spotted gaps and predicted that elements would be found to fill them!

The right-hand column (gases helium, neon, argon, etc) was not yet known.

The periodic table of the elements

Group → / Period ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe

1913-1932: Each atom has electrons orbiting a nucleus made of protons and neutrons bound together by a “strong” force.

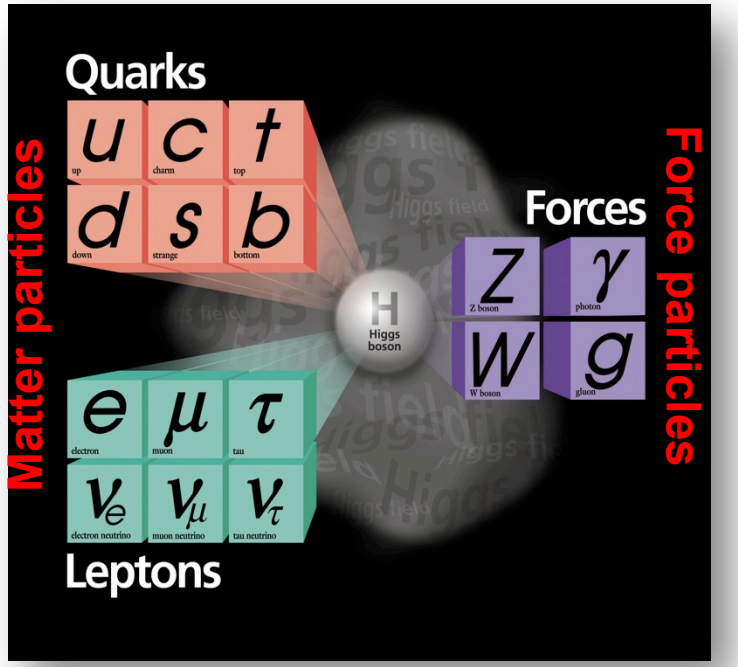


The number of protons in the nucleus determines chemical properties.

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

Physics at the end of 19th century

On the shoulders of giants

Three centuries of physics experiments and theoretical insights led to a monumental scientific corpus:

Classical physics

- Mechanics
- Thermodynamics
- Electromagnetism and Optics

Galileo, Kepler, Newton, Franklin, Ampère, Gauss, Boltzmann, Maxwell, ... and many others

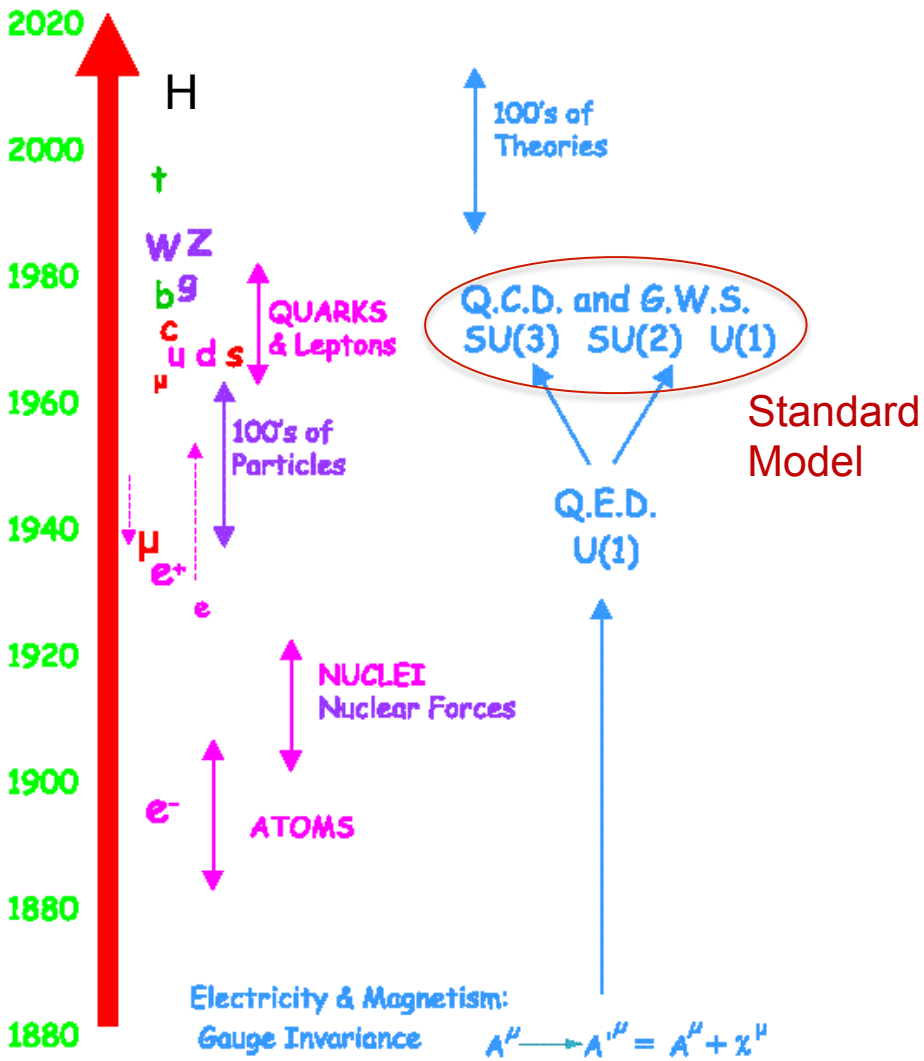
The century of quantum physics

Decisive discoveries in the transition from 19th to 20th centuries:

- X-rays and electron
- Radioactivity: alfa (α), beta (β) and gamma (γ) rays
- The quantum of light
- Special relativity

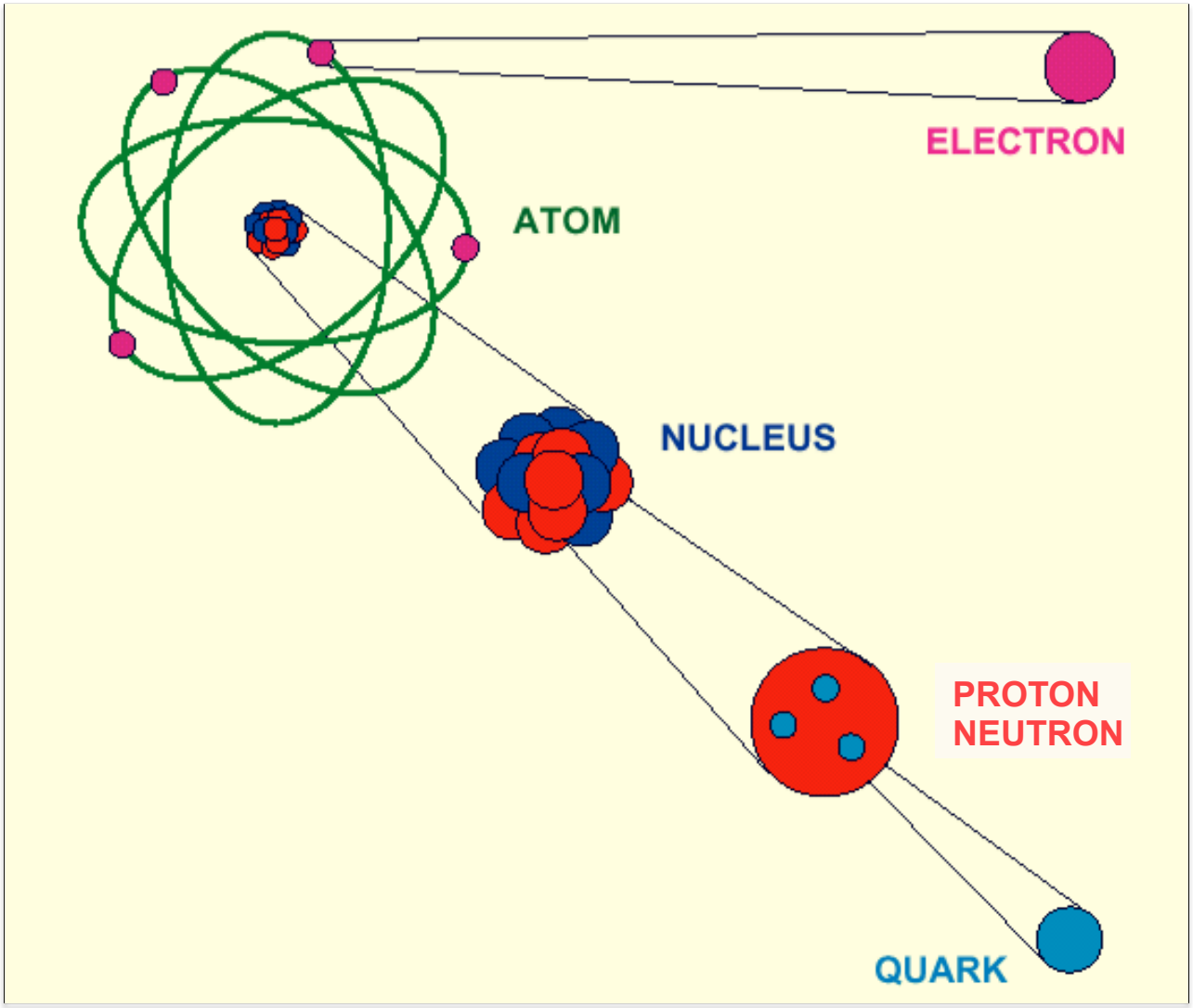
It was the start of
the century of quantum physics

The history of the Standard Model



Parallel experimental and theoretical developments

Constituents of matter



A sense of scale

1×10^{-18} [m]

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

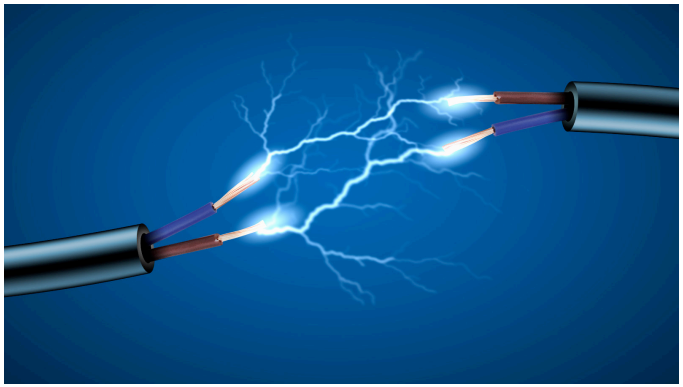
Radioactive decays
Sun
} Weak force

} Electroweak Interaction

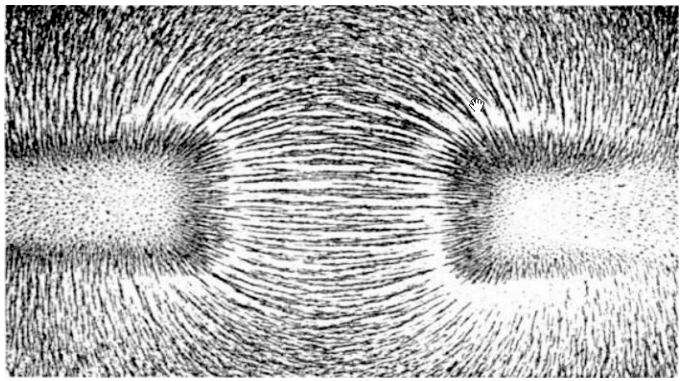
Atomic nucleus
Nuclear energy
} Strong force

Force fields in the 19th century

Gravity force field



Electric force field



Magnetic force field

Iron filings around a bar magnet: can see “field lines” of the magnetic force field.

Electromagnetic force field

Electric and magnetic force fields are different manifestations of a single *electromagnetic* force field.

Radio waves

Microwaves

Light

Ripples in the electromagnetic force field propagate out as waves.

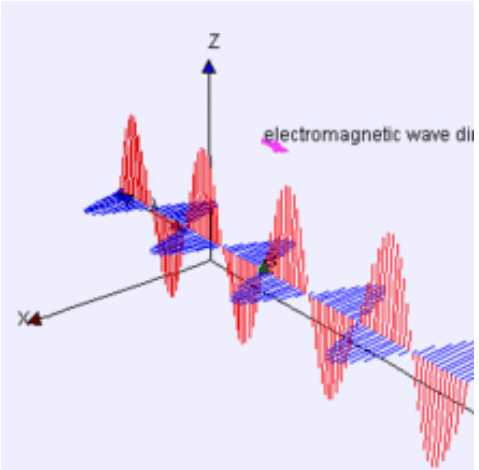
$$\nabla \cdot \mathbf{E} = \frac{\rho_V}{\varepsilon}$$

$$\nabla \cdot \mathbf{H} = 0$$

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t}$$

$$\nabla \times \mathbf{H} = \varepsilon \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E}$$

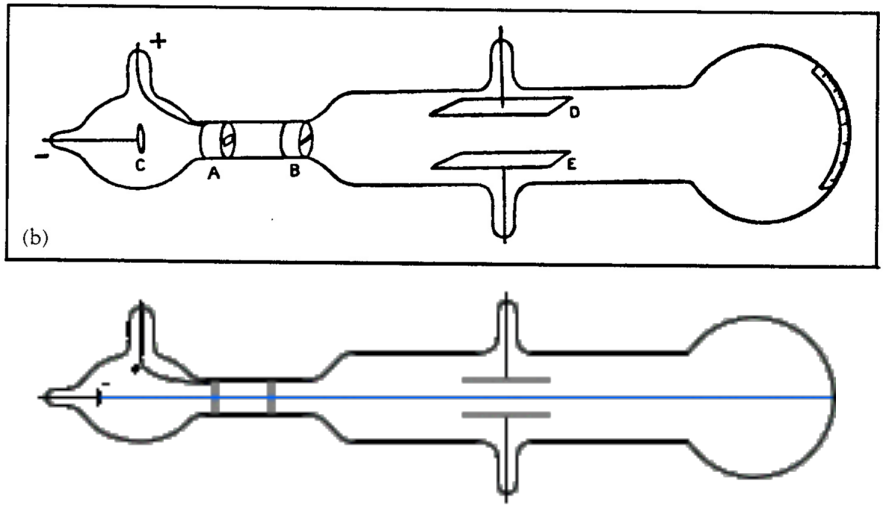
Maxwell equations



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

Measurements

Q electric charge accumulated

$$Q = N.e$$

Heat produced in the impact zone of cathode rays

$$W=N.mv^2/2$$

Deflection of the cathode ray beam in a magnetic field

$$R=mv/Be$$

Result: $e/m=2W/QB^2R^2 = 2{,}3.10^{17}$ **esu/erg**

Discovery of x-rays

In 1895, Röntgen noticed a penetrating radiation produced in the operation of cathode ray tubes.

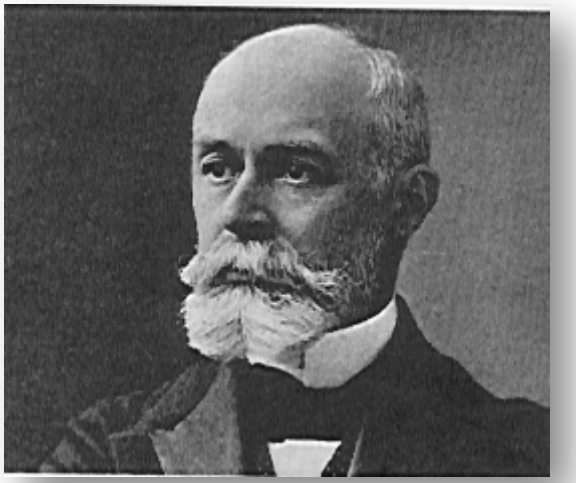
Röntgen was able to fix images on photographic plates, sensitive to the new radiation called x-rays.

Progressively grew the idea that x-rays are electromagnetic radiation of very small wavelength.

The speed of propagation was first measured in 1905 by Erich Marx. Equal to speed of light.

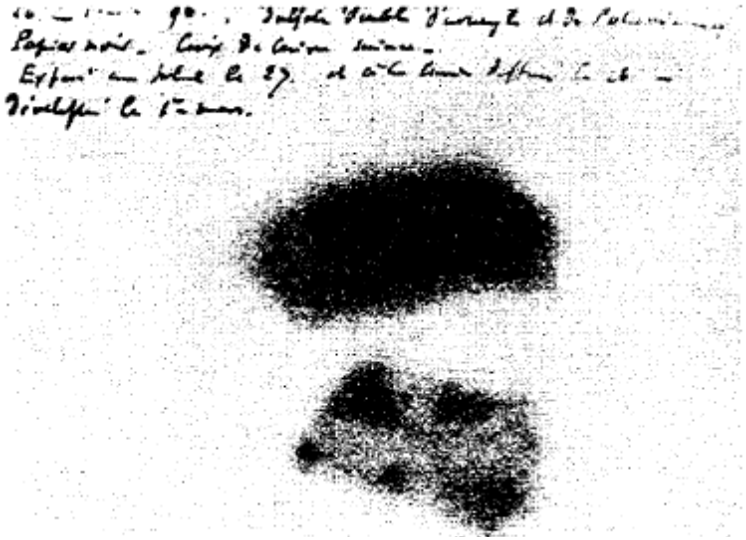
Discovery of radioactivity

In 1896 Henri Becquerel discovered that the uranium salt emits spontaneously penetrating radiation



Uranium salt is fluorescent: after exposer to Sun emits light seen in the dark

"Photograph" by Becquerel in Paris

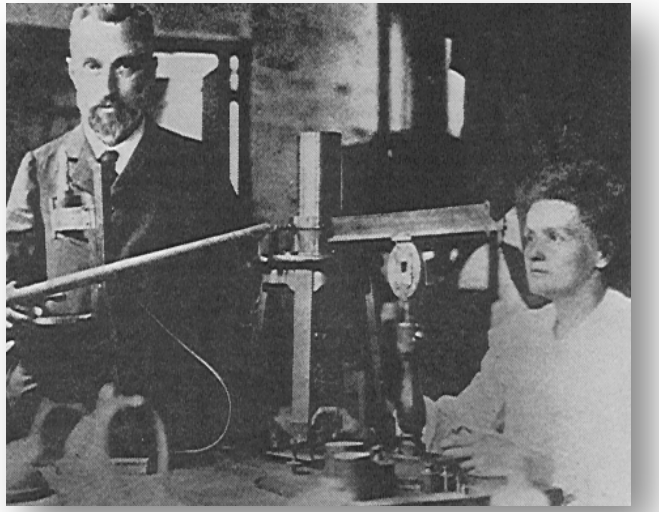


Film was in a drawer, in black paper with uranium on top.

Image was created by high-speed electrons, named beta rays

Marie Curie and radioactive elements

Marie Curie found that the emission of radiation is a property of uranium and other elements.



Marie and Pierre Curie isolated a small highly radioactive residue, containing a new element designated by Polonium.

Shortly after isolated another strongly radioactive element that was called Radio

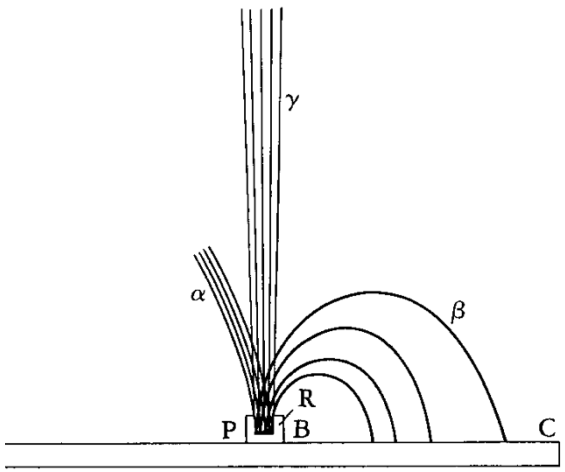
alpha, beta, gamma rays

In 1898 Ernest Rutherford established the existence of two different types of radiation emitted by uranium, known as alpha and beta rays.

In a few years it was found that the beta rays are electrons.

Later it was shown that the alpha rays are ionized atoms of Helium.

Paul Villard discovered a third form of radiation called gamma rays (γ). Gamma rays are electromagnetic radiation of very small wave length.



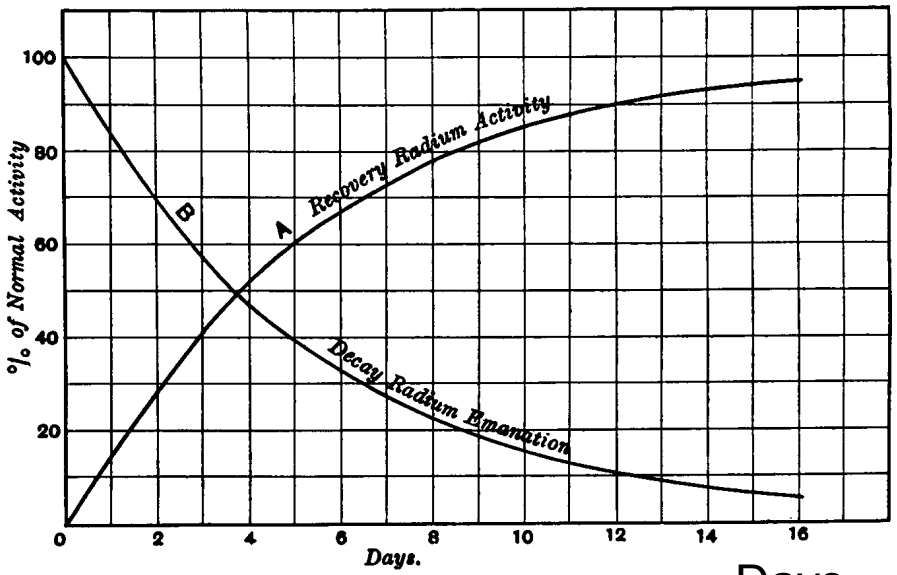
The three types of radiation, α, β and γ, have distinctive paths in a magnetic field.

[Marie Curie thesis (Paris: Gauthier-Villars, 1904)].

The transmutation of elements

Transmutation of elements was first observed by Rutherford: atoms of ^{238}U decaing to ^{234}Th (emitting an alpha particle)

Activity



Days

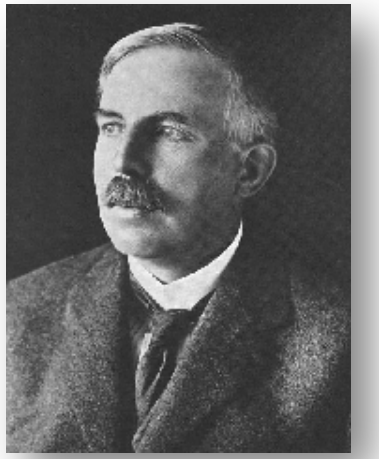
Radioactivity of precipitate decreases (Th decays)
Radioactivity of the solution reappears (U decays)

Fundamental law of decay processes :

Each radioactive atom has a constant probability of decaying per unit time.

The Rutherford experiment

Around ~1900, common thinking was that the atom was like a plum pudding, with positive and negative charges uniformly distributed.



Ernest Rutherford
1871-1937

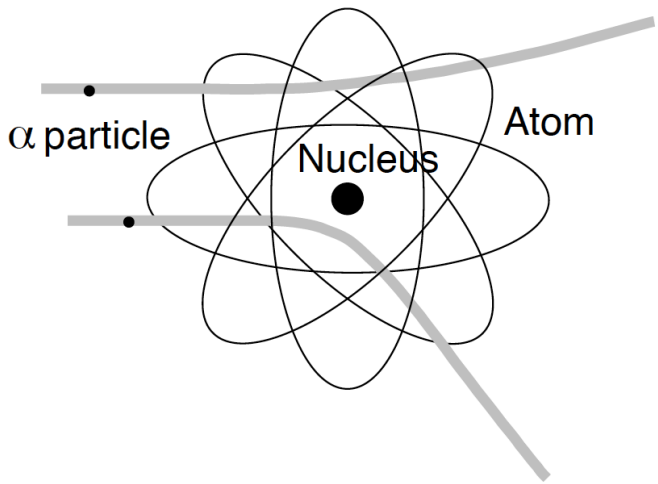
Awarded the
Nobel Prize in 1908

Experiment:

Alpha particles with kinetic energy of 5 MeV resulting from the decay of polonium are sent on a very thin gold foil.

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

Calculations with 'plum pudding' model:
Deflection at large angles are extremely unlikely, contradicting experimental results



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

Rutherford atomic model

New model of the atom

Protons are concentrated in the **nucleus**

Electrons are dispersed in the volume of the atom, orbiting around the nucleus.

If we drew the atom to scale and made protons and neutrons a centimeter in diameter,

then the electrons and quarks would be less than the diameter of a hair

and the entire atom's diameter would be greater than the length of thirty football fields!

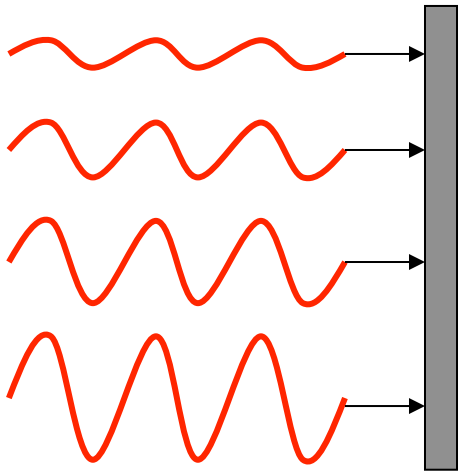
99.999999999999% of an atom's volume is just empty space!

Photoelectric effect

Experimental observation:

Electrons are emitted from matter when light is incident

Increase energy of light by increasing amplitude



electrons emitted ?

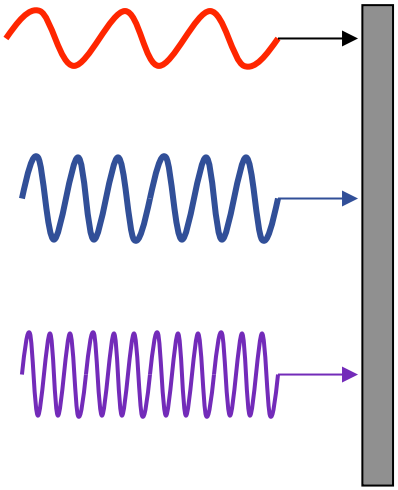
No

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, each with an energy proportional to the frequency of the 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 $E = h\nu - W$.

h - Plank constant ν - wave frequency

Einstein, Annalen der Physik, 1905

6. *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt;*
von A. Einstein.

Es scheint mir nun in der Tat, daß die Beobachtungen über die „schwarze Strahlung", Photolumineszenz, die Erzeugung von Kathodenstrahlen durch ultraviolettes Licht und andere die Erzeugung bez. Verwandlung des Lichtes betreffende Erscheinungsgruppen besser verständlich erscheinen unter der Annahme, daß die Energie des Lichtes diskontinuierlich im Raume verteilt sei. Nach der hier ins Auge zu fassenden Annahme ist bei Ausbreitung eines von einem Punkte ausgehenden Lichtstrahles die Energie nicht kontinuierlich auf größer und größer werdende Räume verteilt, sondern es besteht dieselbe aus einer endlichen Zahl von in Raumpunkten lokalisierten Energiequanten, welche sich bewegen, ohne sich zu teilen und nur als Ganze absorbiert und erzeugt werden können.

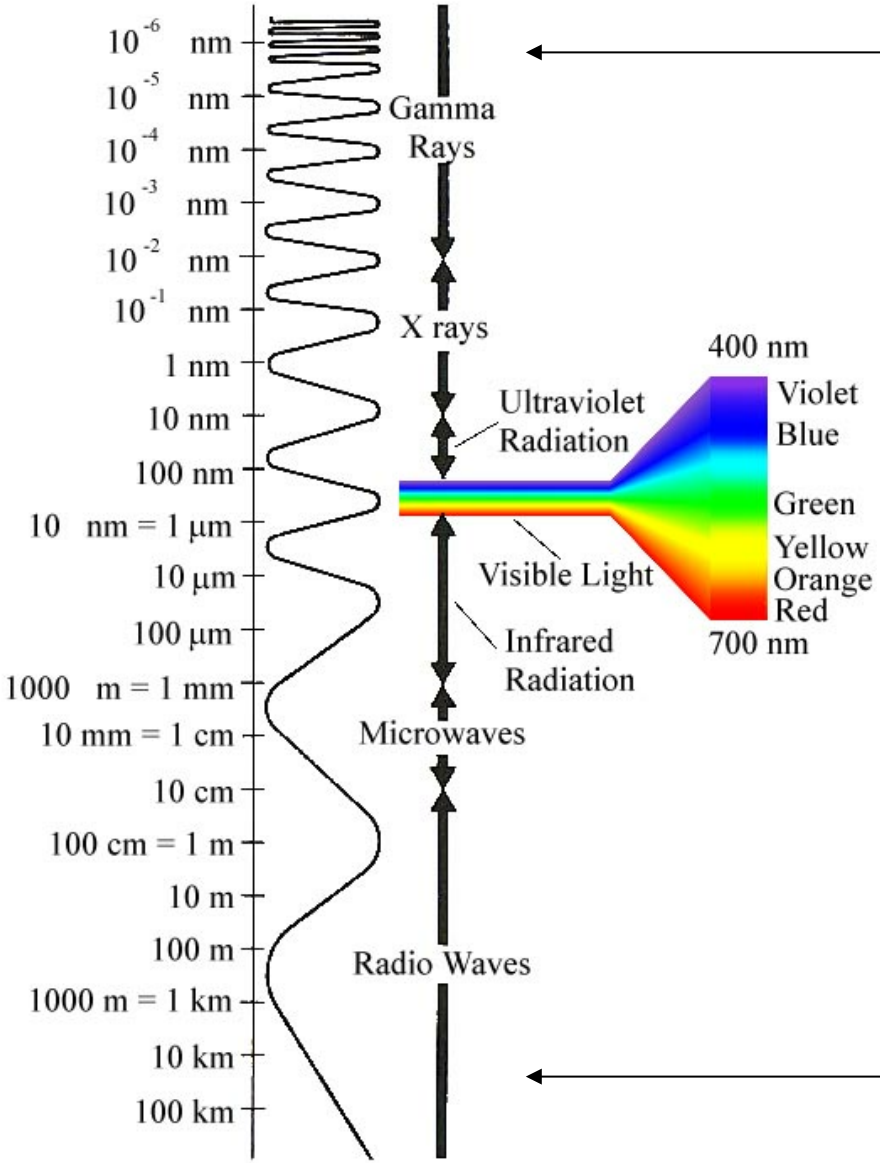
Nobel Prize in 1921

"It seems to me that the observations are more readily understood if one assumes that the energy of light is discontinuously distributed in space… The energy of a light ray consists of energy quanta which are localized in space, which move without dividing, and which can only be produced and absorbed in complete units."

Translation: Arons and Peppard, Amer. J. Phys. 1965

Swiss citizen Albert Einstein working in Berne, Switzerland.

The electromagnetic spectrum



Shortest wavelengths
(Most energetic photons)

$$E = h\nu = hc/\lambda$$

E - energy
ν - wave frequency
λ - wavelength
h - Plank constant
c – speed of light

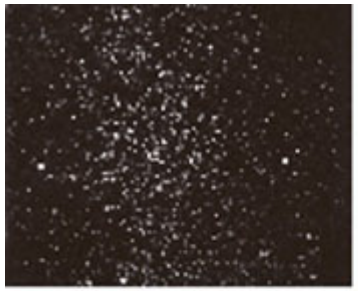
Longest wavelengths
(Least energetic photons)

Photons, digital camera & images

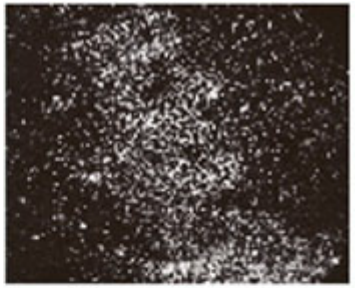
Using a digital camera with many pixels (~10 M pixels)

Very small pixels gives fine image resolution (10 μm)

The individual spots on this images are the actual result of individual photons striking the pixel array



~3000 photons



~10,000 photons

~100,000 photons

~1 M photons

~4 M photons

~30 M photons

Particles and waves

In 1923, Louis de Broglie made a decisive contribution to the development of quantum theory, by suggesting that particles of matter, as the electron, have a dual nature - particle and wave - like electromagnetic radiation.

Louis de Broglie

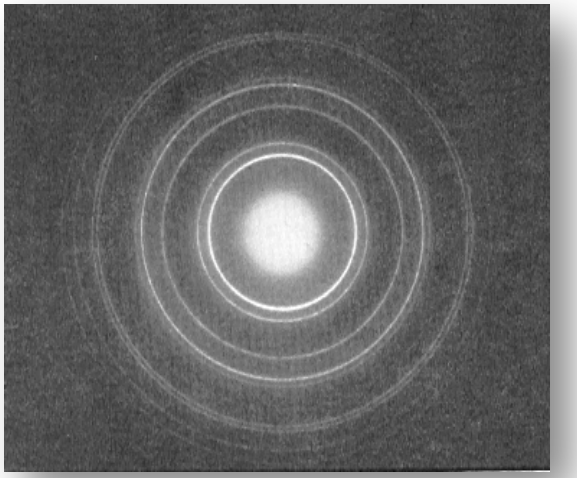
Particle **energy** in terms of wave **frequency**

$$E = h\nu$$

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

$$p = h/\lambda$$

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



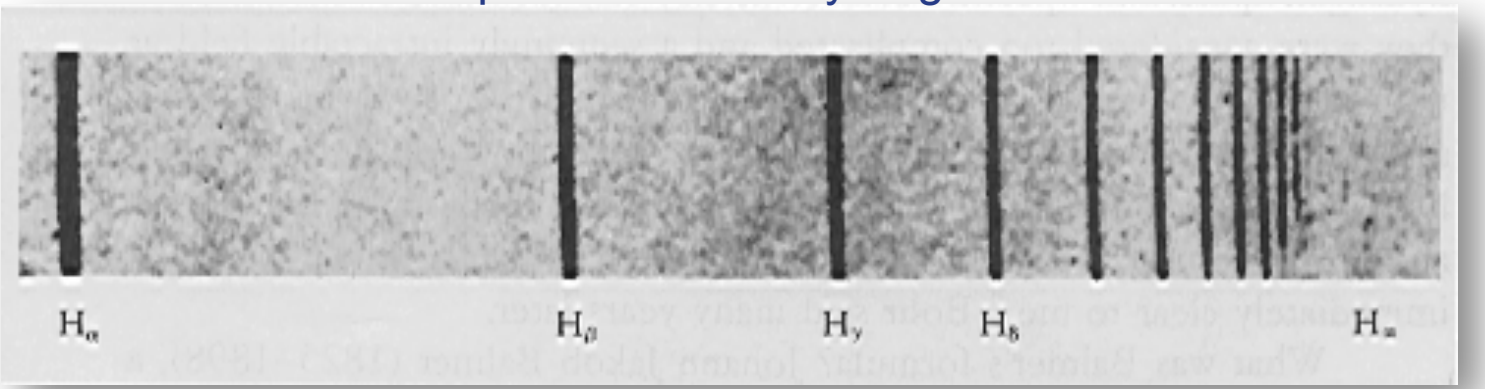
Electron diffraction

The atomic spectra

Arnold Sommerfeld, 1919, in the preface to his work ' Atombau und Spectrallinien ':

"Since the discovery of spectral analysis, nobody could doubt that the language of the atom would be understood if one could interpret the Atomic Spectra".

The spectrum of the hydrogen atom.



The observations of atomic phenomena showed systematically the existence of discrete physical quantities, quantities that can only take certain quantized values.

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;

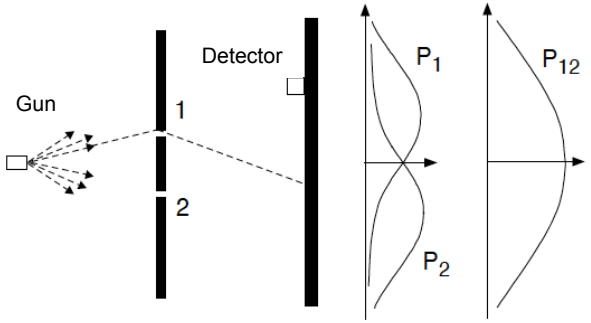
b) each quantum state corresponds a certain energy of the electron, and these energies can only take certain discrete values;

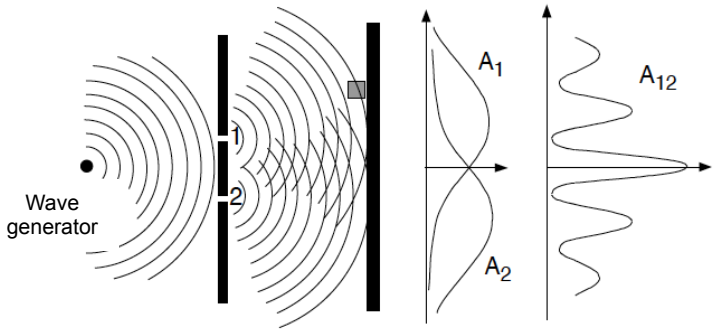
c) when in an excited state, the atom decays to the ground state emitting a photon of energy equal to the difference of the two states.

1885-1962

Awarded the Nobel Prize in 1922

Quantum physics is weird

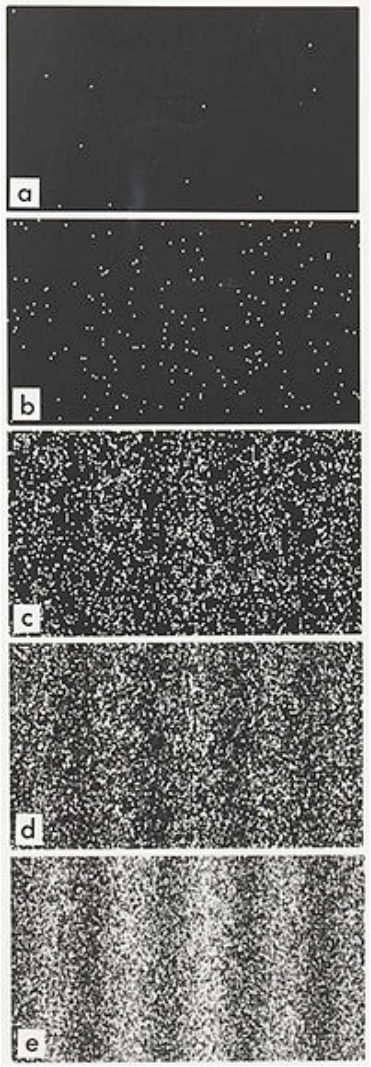




Shooting electrons into a screen with two slits

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

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



Electron buildup over time

Quantum probabilities

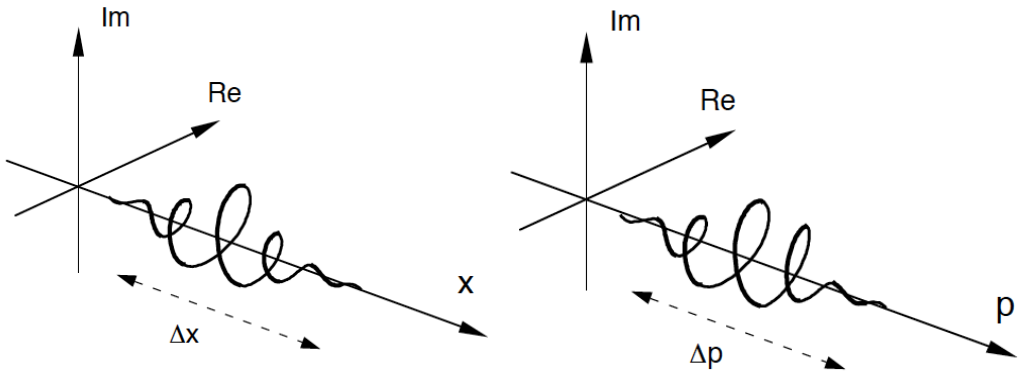
A **quantum particle** is described by an infinite number of **probability amplitudes** for the endless points of space.

This collection of probability amplitudes form the quantum state of the particle and is represented by a function $\Psi(x)$, the **position wave function** of the particle.

The **momentum wave functions $\Psi(p)$** describes the probability to measure a given value of momentum p.

The wave formulation of quantum mechanics is closely linked to the uncertainty principle of Heisenberg:

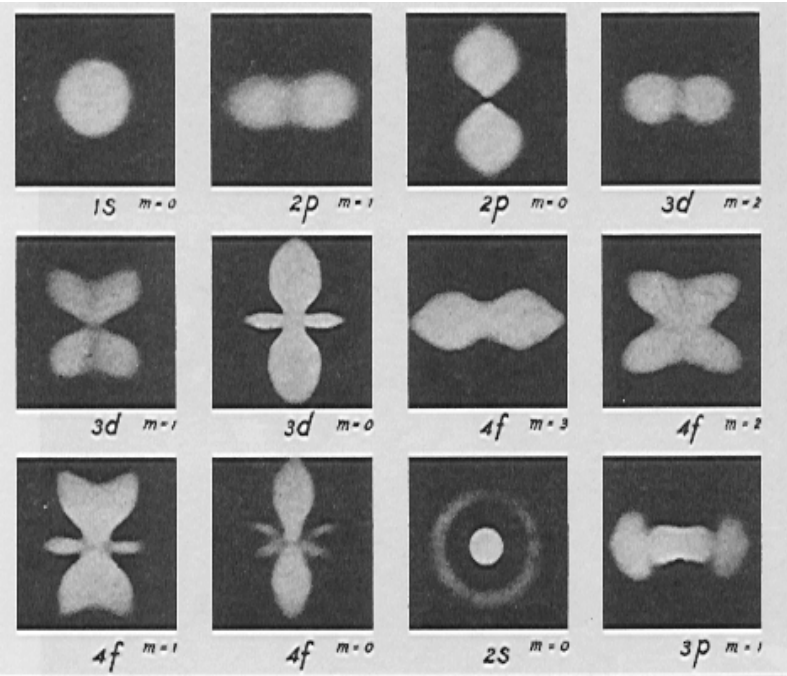
The quantum uncertainties Δx e Δp obey the relation: $\Delta x.\Delta p>h$



Position and momentum wave functions

The Schrödinger equation

In 1925 Schrödinger found an equation with which he could determine the quantum wave function.



Wave functions of the electron in the hydrogen atom

He applied his equation to the case of a single electron in the electrical field created by a proton (Hydrogen atom).

The equation leads to quantized energy levels of the hydrogen atom.

The numeric values coincide with the experimental data.

The spin of particles

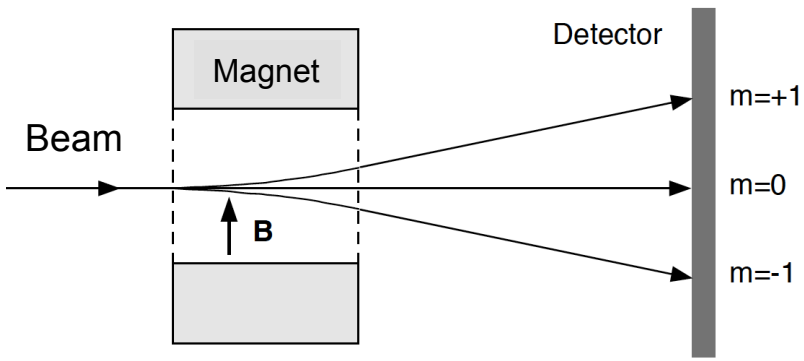
Some particles have intrinsic angular momentum, called spin.

[It is like a planet spinning on its axis

but in classical physics point particles have zero angular momentum]

Spin can have integer (0, 1, 2, …) or half-integer values (1/2, 3/2, 5/2, …)

Spin is a vector quantity, and so has both magnitude and direction. The vector components of a particle's spin can only assume certain discrete values.



The Stern and Gerlach experiment

On the experience of Stern and Gerlach a beam of atoms with angular momentum L passes through a magnetic field.

The L_z component of angular momentum vector has only three possible values:

$$L_z = +1,\ L_z = 0 \text{ ou } L_z = -1$$

Bosons and fermions

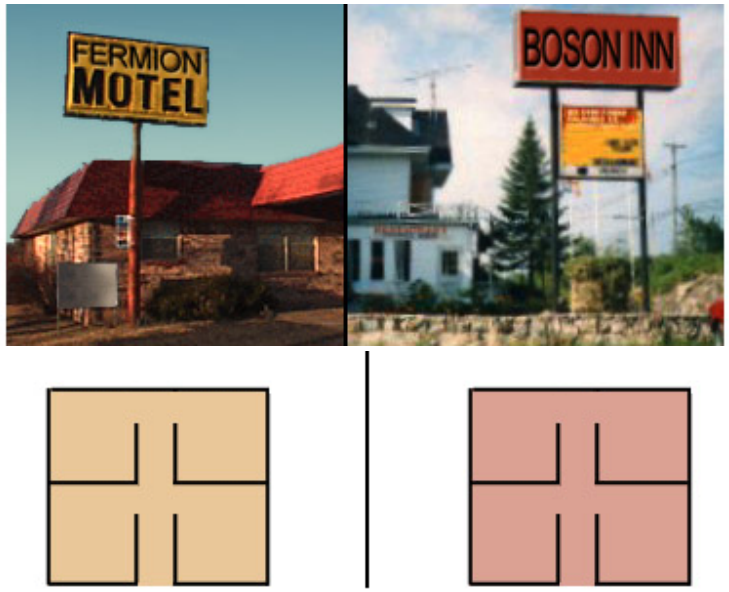
S. N. Bose

Particles with integer spin are called bosons.

Particles with half-integer spin are called fermions.

Due to a deep Quantum-Mechanical effect:

- **Bosons** tend to clump together in the lowest energy quantum state
- Two or more identical **fermions** cannot occupy the same quantum state (Pauli exclusion principle)



Important consequence of the exclusion principle is the electron shell structure of atoms, explaining the variety of chemical elements.

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

Cosmic rays

Occasionally energetic particles enter our atmosphere from outer space 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

Particles emitted from radioactive sources have of the order of one MeV (1 MeV=10^6 eV)

Energy cosmic rays can reach thousands of GeV (1 GeV=10^9 eV)

Particle detectors

During the first quarter of the 20th century emerged some technical innovations that strongly influenced the course of particle physics

Cloud Chamber: 1911, C.T.R. Wilson (Nobel Prize)

Vapors condensate into tiny droplets around ionized atoms along charged particle trajectories

Geiger-Muller counter:

Charge particles induce electrical discharges between two electrodes in a gas

Coincidence circuit: (B. Rossi)

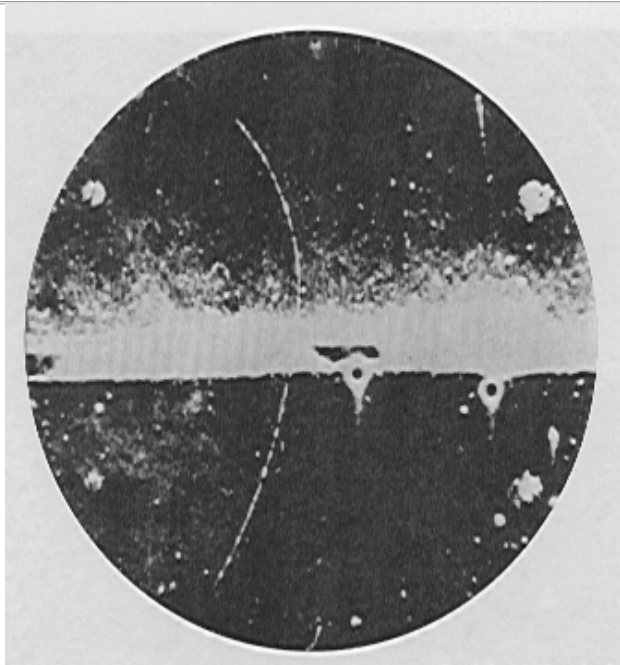
the first ancestor of modern logic circuits used in computers.

Cascade of particles produced by cosmic rays, photographed in a cloud chamber controlled by a Geiger counter

Discovery of antimatter

In 1932, Carl Anderson found particles with positive charge that could not be protons because the density of bubbles was too small.

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



Positron photographed in a Cloud Chamber under a magnetic field.

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

Non-relativistic energy: $$E = \frac{m\,\mathrm{v}^2}{2} = \frac{p^2}{2m}$$

Relativistic kinetic energy (Einstein):

$$E^2 = m^2c^4 + p^2c^2 \qquad E = \pm\sqrt{m^2c^4 + p^2c^2}$$

Negative solution is related to the existence of antimatter

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
Unlike muons they do interact with nuclei
Decay to another meson, the muon

Discovery of kaon meson (K)

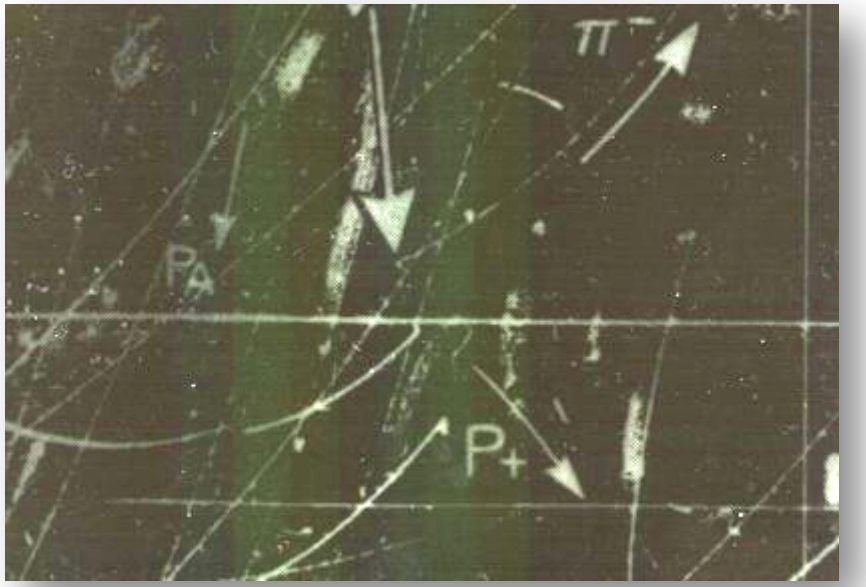
Discovery of strange meson (kaon) Butler 1947

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

Drawbacks of Cosmic Rays:

- Interesting interactions happen very rarely
- Very difficult to catch them in particle detectors
- Rate drops quickly with particle energy

Particle accelerators:

- Accelerate ordinary stable particles (e, p) from rest to large kinetic energy and smash them into matter
- Make things happen when and where we want
- Can achieve high rates at high energies

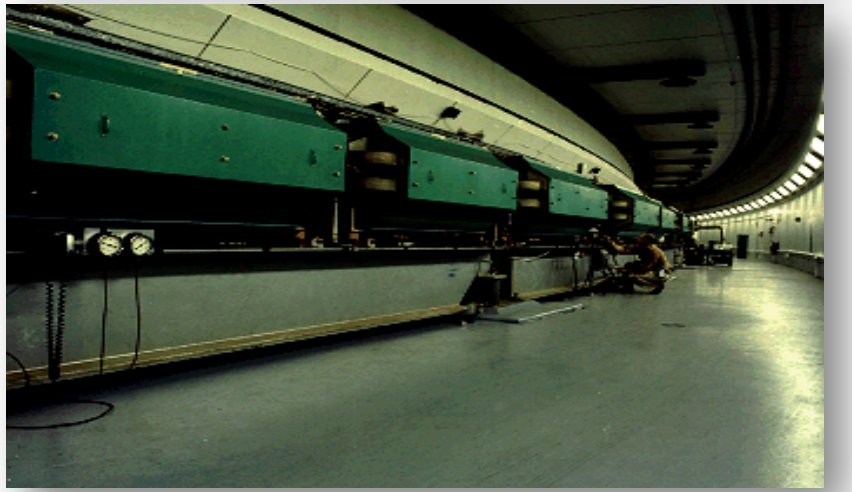
Kinetic energy of light particles can be turned into mass of heavy particles!

$$E = m c^2$$

Particle accelerators

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

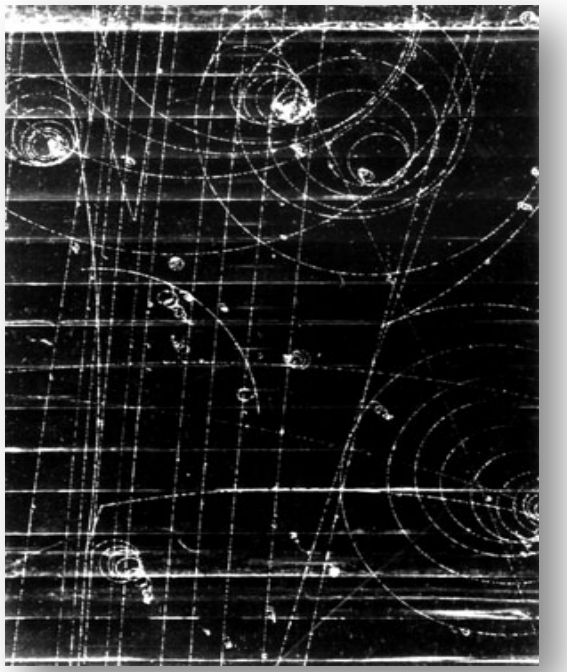
– e.g. Cosmotron at Brookhaven (first proton synchrotron 1952 - 2.3 GeV)

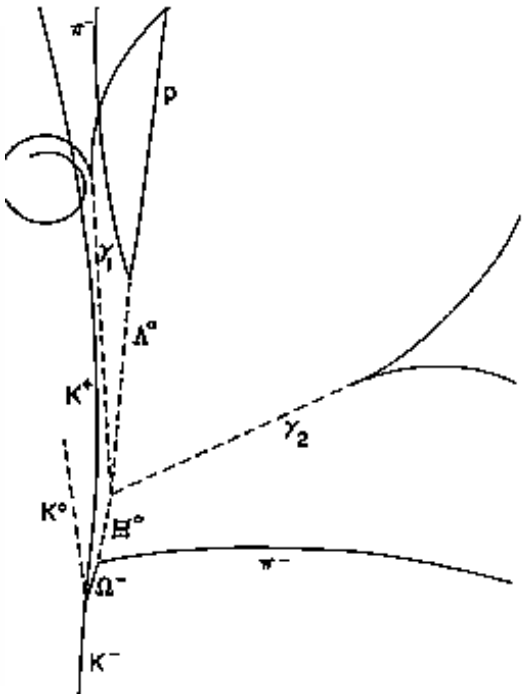


– Replaced by AGS in 1960's

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)





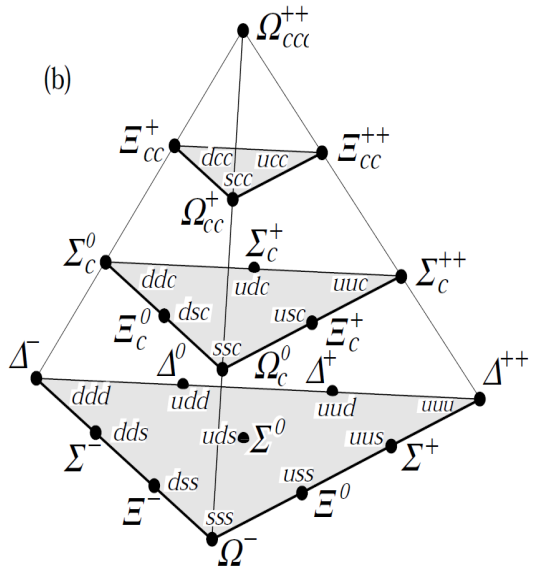
Hadron tables

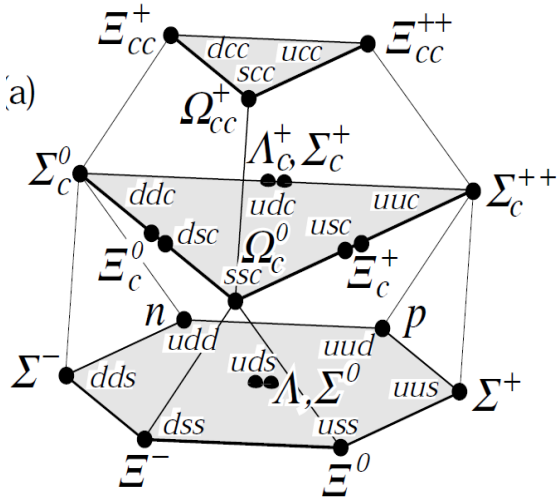
Physicists discovered dozens of "elementary particles" similar to the proton and neutron.

Tables had gaps, the whole periodic table story repeats one level down.

Lesson from Mendeleev periodic table:

Objects were divisible into smaller objects!





Quarks! up, down, strange…

Gell-Man, Zweig 1964

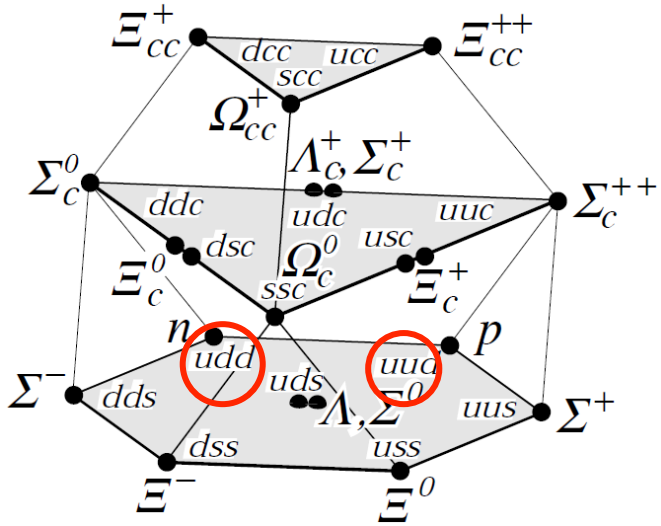
A SCHEMATIC MODEL OF BARYONS AND MESONS

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.



- 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

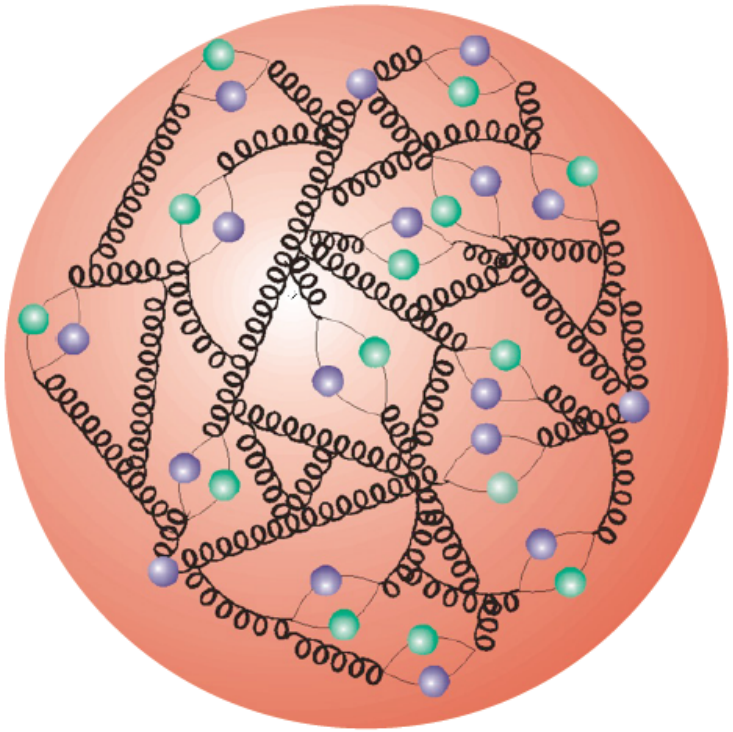
Quark model was confirmed experimentally in 1968 by a Rutherford-type experiment at SLAC (Friedman, Kendall, Taylor)

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

Two quarks in the proton behave as two objects linked by a rubber band:

- when the two objects are close, the elastic band is loose and the force is zero;
- when the two bodies are pulled apart, the tension of the elastic increases as the distance increases.

No free quark has ever been observed:

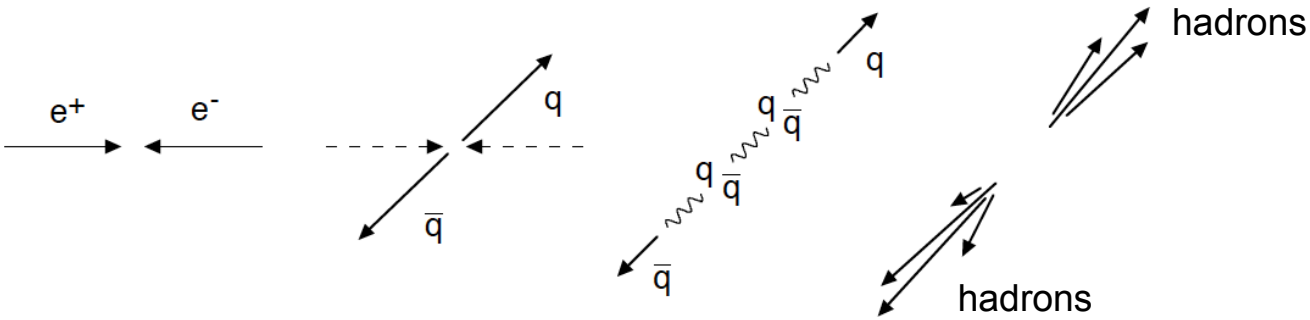
Quarks, antiquarks and gluons are confined inside mesons and baryons

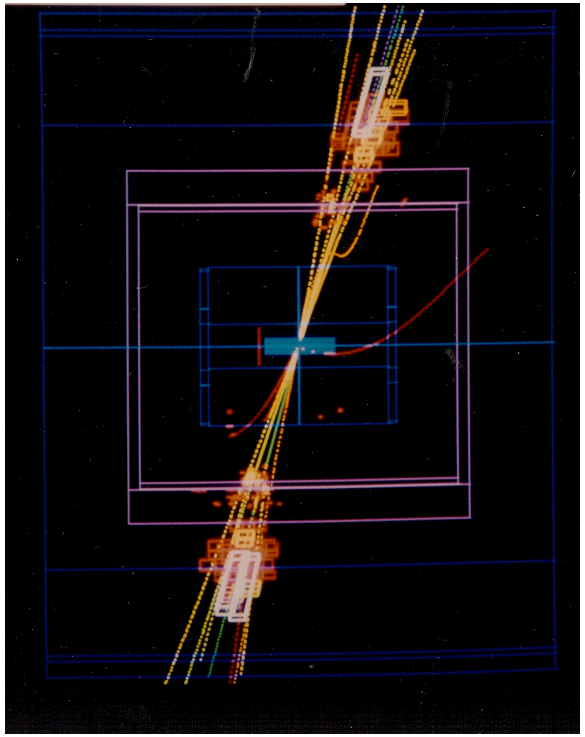
The strength of the strong interaction grows with distance:

- 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.

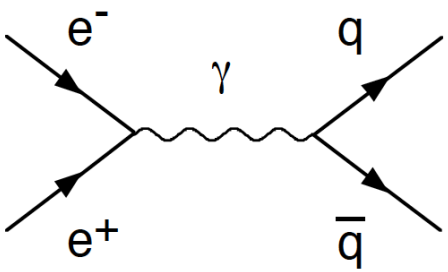
QCD at work: Jets of particles

The experiments of e^+e^- annihilation in the late 70's and the 80's, in the colliding rings in Hamburg and at Berkeley, showed that the hadrons resulting from these collisions are grouped into two or more jets of particles concentrated in certain directions of space.

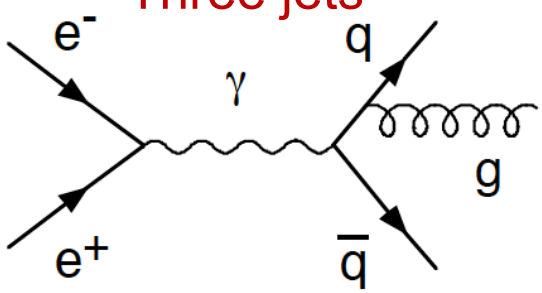




Two jets



Three jets



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 and given by:

$$E = c^2 \cdot (m_A^2 - m_B^2 + m_e^2)/(2\, m_A)$$

m_A , m_B - mass of nuclei A e B, *me - electron mass, and c - speed of light*

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 the Solvay Congress of 1933 E. Fermi, at this time still a young men, proposed his famous 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.**

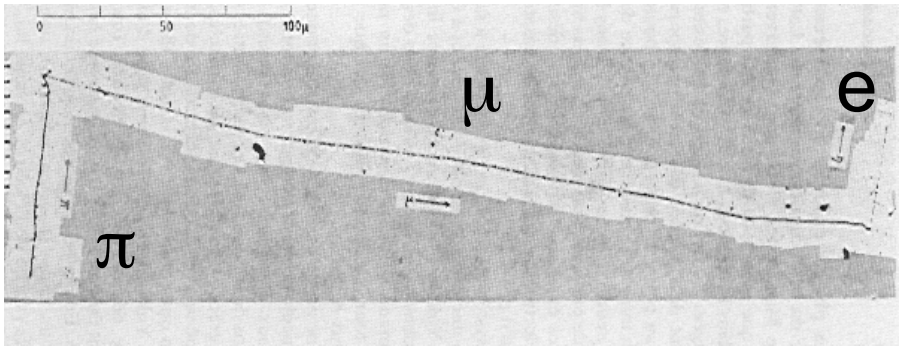
Enrico Fermi

The discovery of the muon

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

Neddermeyer, Anderson (1936) concluded that these penetrating particles could not be protons, electrons or positrons, but a 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

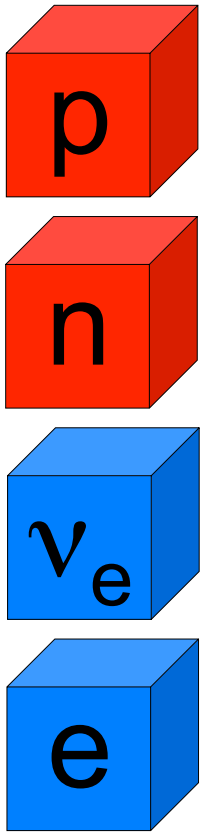
$$\mu^- \rightarrow \nu_\mu \, e^- \, \nu_e$$

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

Nobel laureate I. I. Rabi: "Who ordered that?"

The smallest building blocks of matter?

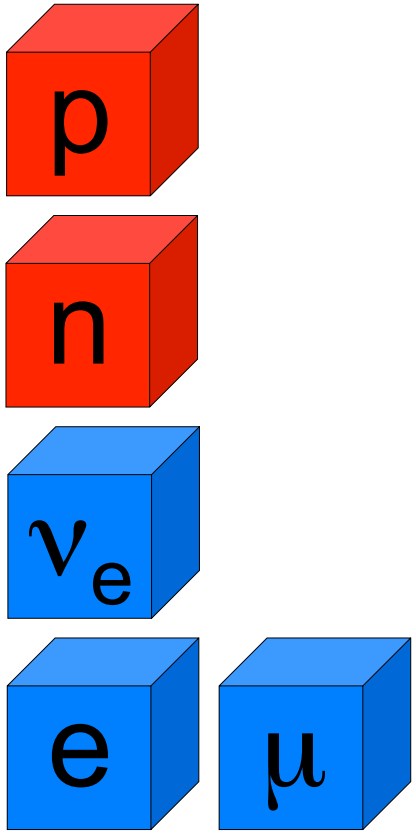
Before muon discovery → After muon discovery



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

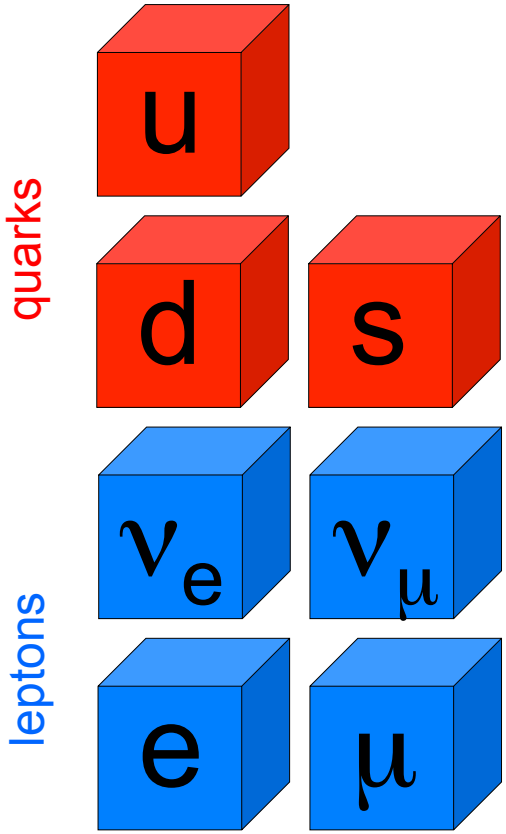
It was the first evidence of the mystery of the particle generations

77 years later the mystery is still with us



The smallest building blocks of matter?

In 1964 the quark model changed the table:



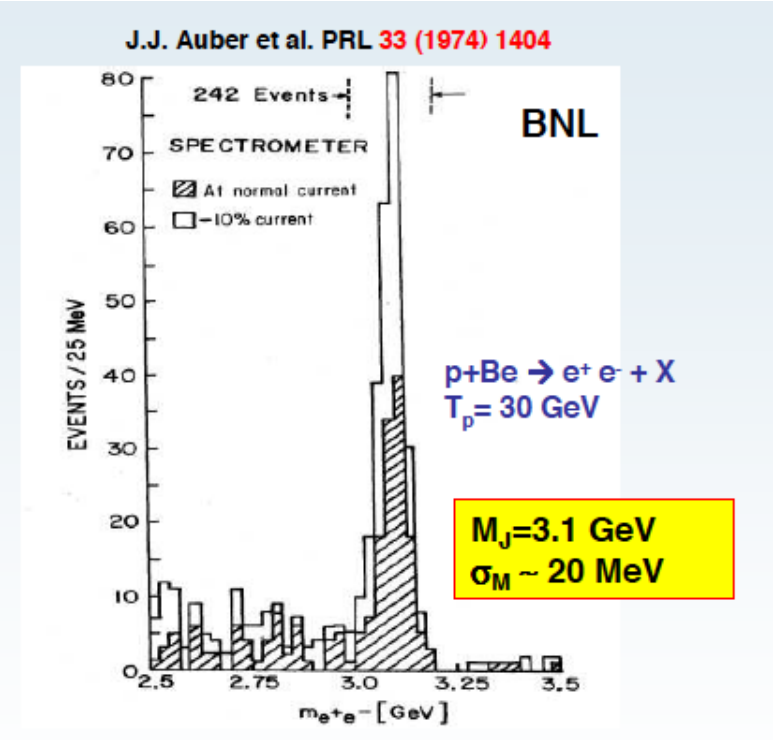
Is one piece missing?

Charm quark discovery

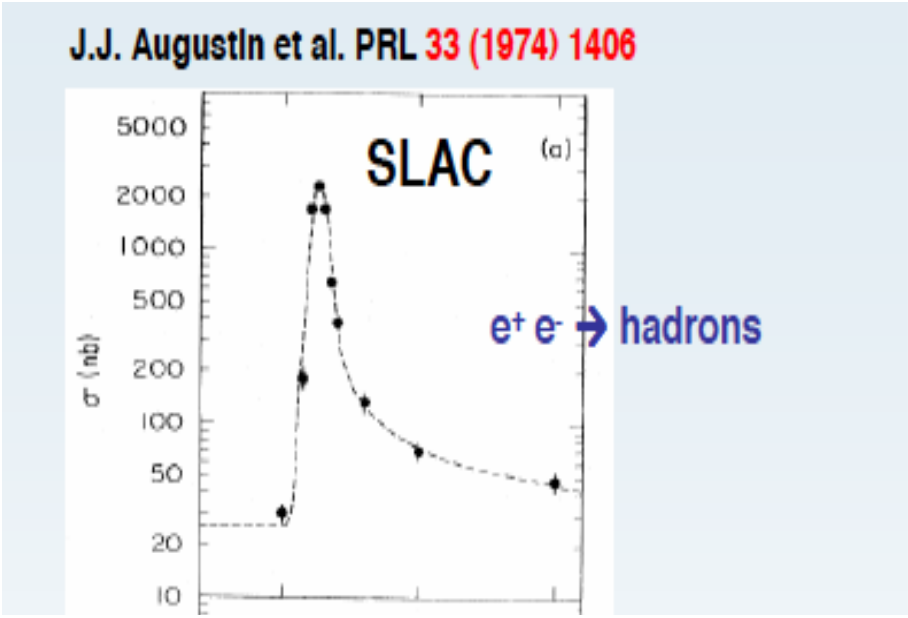
J/Ψ discovery – the 1974 "November Revolution"

The new particle is composed of charm and anti-charm

Ting, Richter 1974



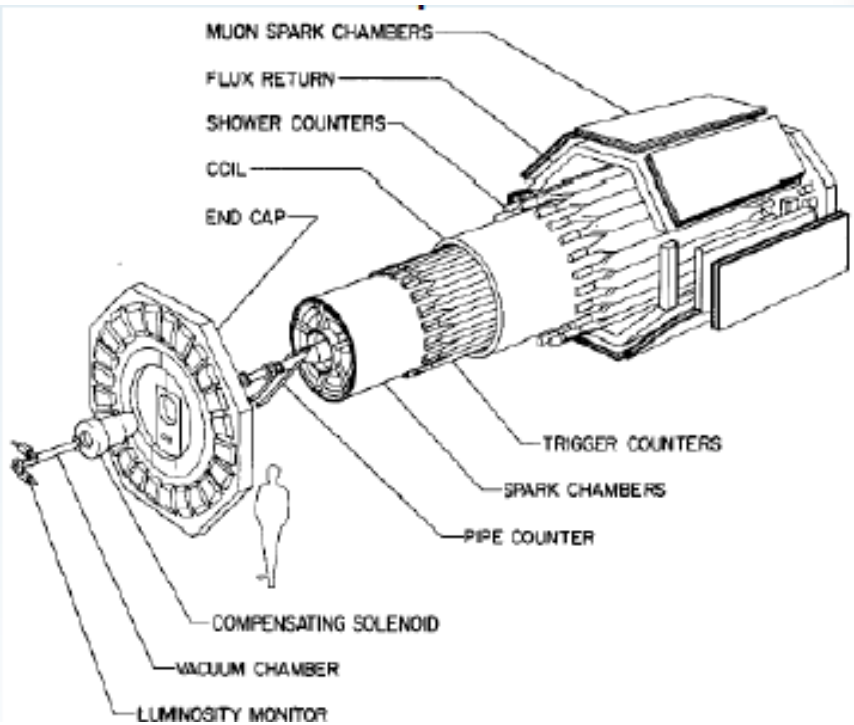
Proton beam at AGS, Brookaven

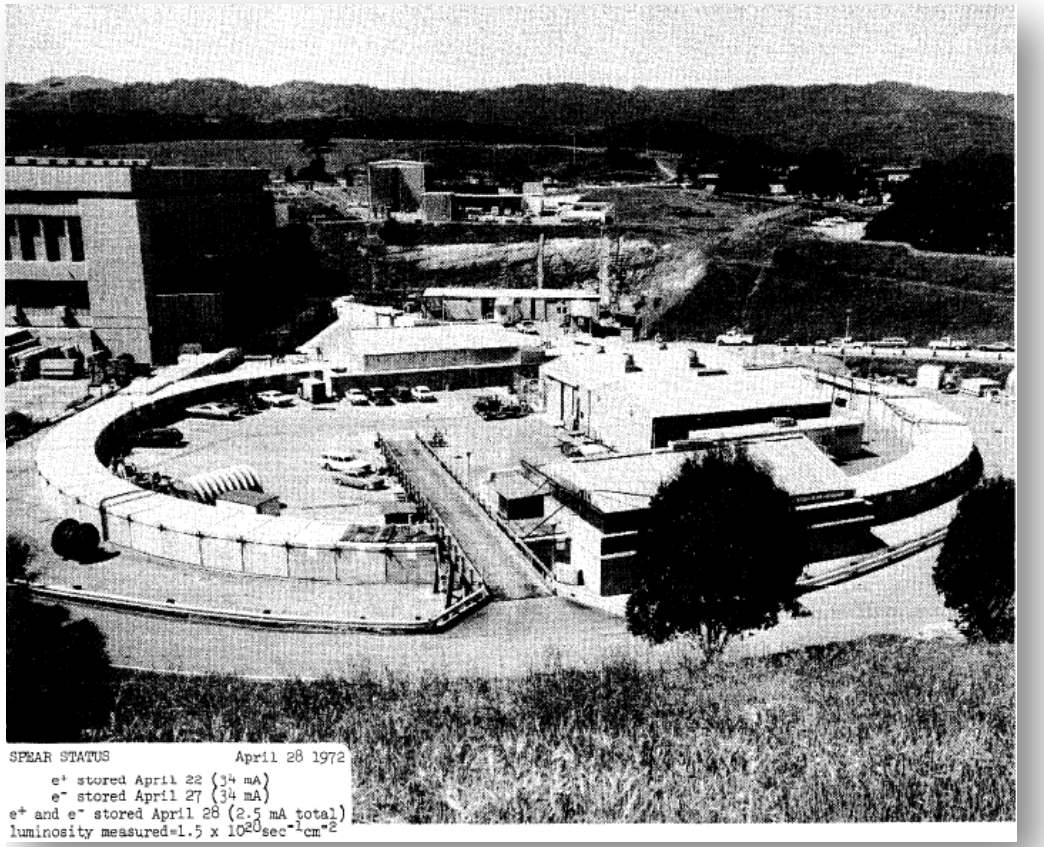


Electron-positron collider SPEAR, SLAC, Stanford

SPEAR e+e- collider

MARK I detector

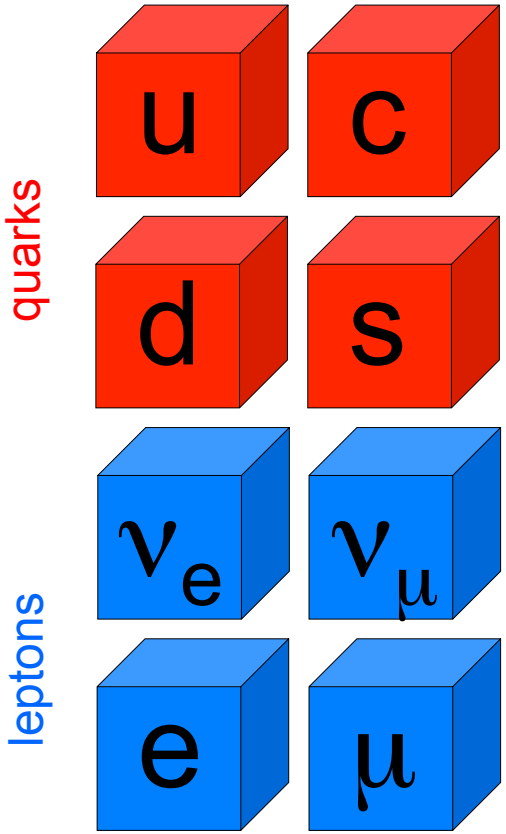




SLAC, Stanford

The smallest building blocks of matter?

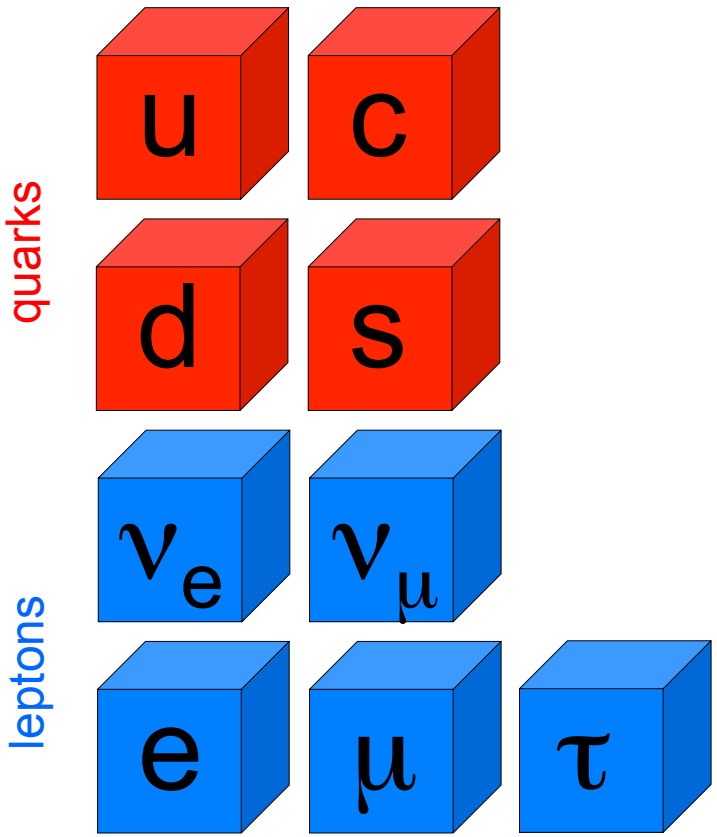
… and it became



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_τ~1.8 GeV
- Discovery of **bottom quark** Lederman 1977
  - m_b~4.7 GeV
- Discovery of **top quark** Fermilab 1995
  - m_t~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:

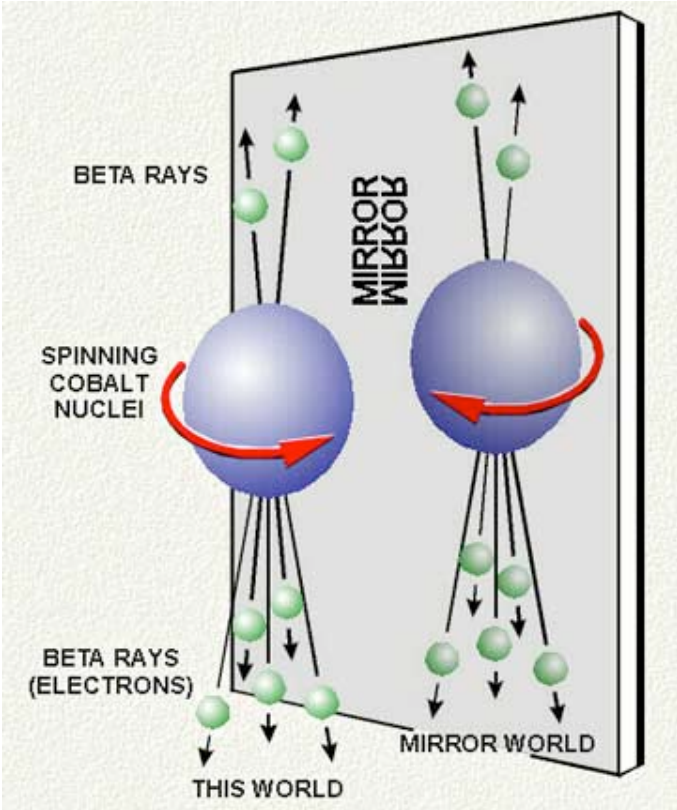
$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

Clyde Cowan conducting the neutrino experiment 1956

Mirror asymmetry

Parity symmetry

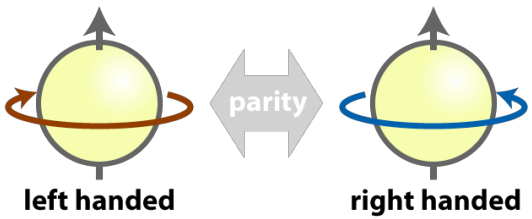
This principle says, in short, that the mirror image of a physical process has equal probability of being observed in nature.



In 1957 it was discovered that the weak interaction violates the parity symmetry:

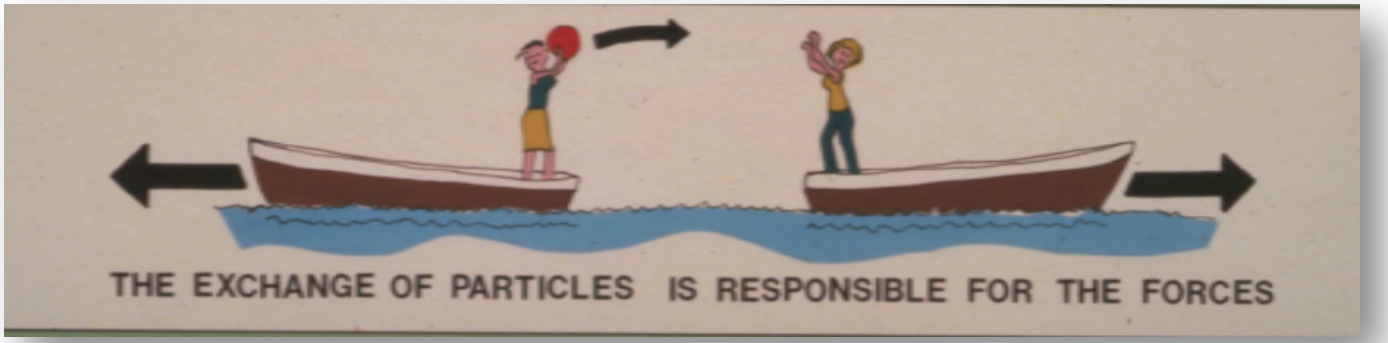
the beta decay of cobalt nuclei in a magnetic field is not symmetric, electrons are emitted preferentially from one of the poles

In nature there are only left-handed neutrinos (and right-handed antineutrinos)!



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.



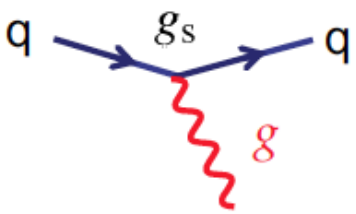
The quantum theory does not invalidate the classical theory, but restricts its scope:

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

Standard model interactions

The interaction of gauge bosons with fermions is described by the Standard Model

STRONG

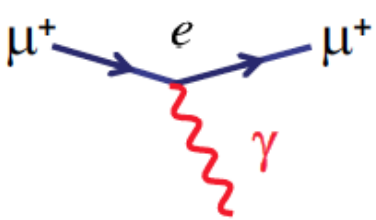


Only quarks

Never changes flavour

$\alpha_S \sim 1$

EM

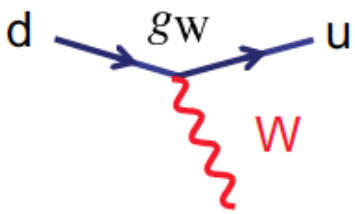


All charged fermions

Never changes flavour

$\alpha \simeq 1/137$

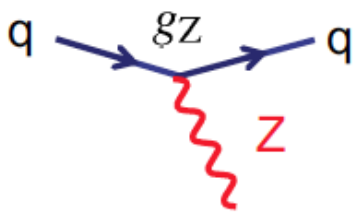
WEAK CC



All fermions

Always changes flavour

WEAK NC



All fermions

Never changes flavour

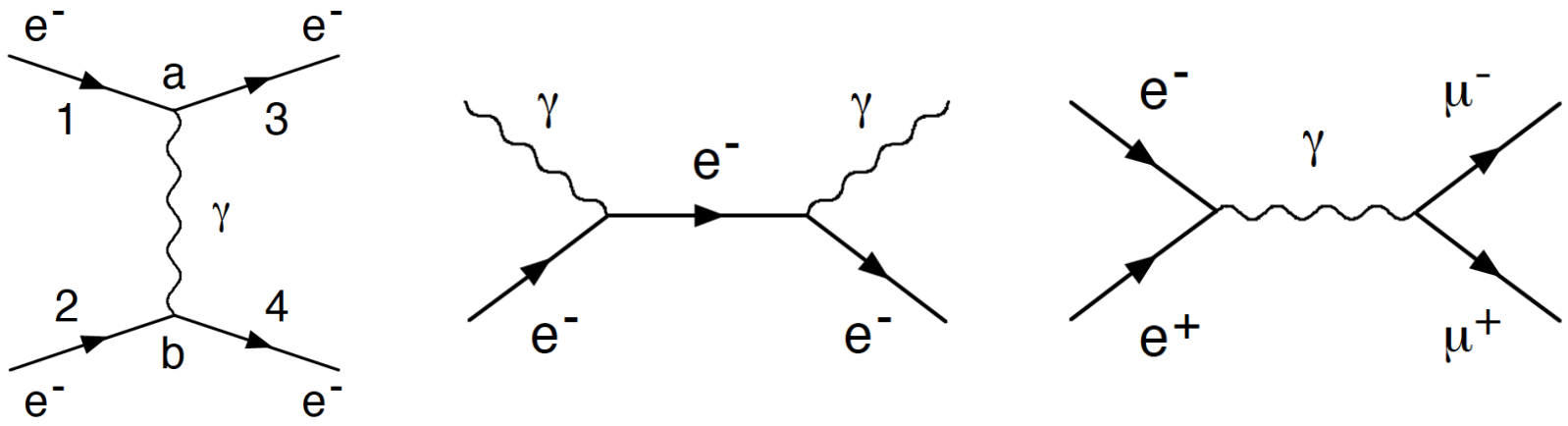
$\alpha_{W/Z} \sim 1/40$

Gluons	Photon	W+, W-	Z^0
massless	massless	very massive	very massive

Feynman diagrams

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

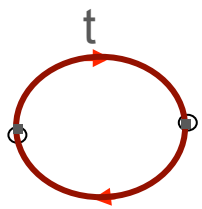
In the fifties, Richard Feynman introduced the **Feynman diagrams** which are pictorial representations of the mathematical expressions governing the behavior of particles interactions.



Quantum field theory

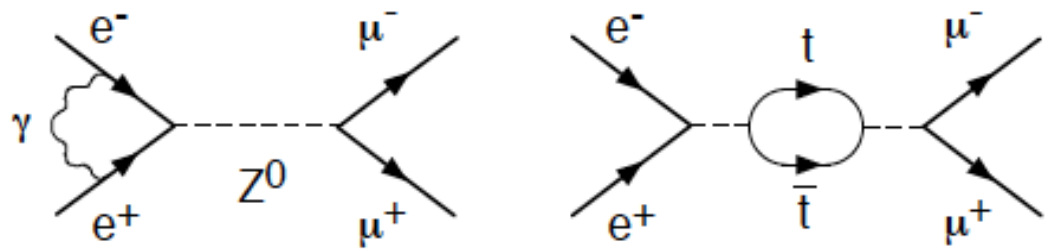
A particle-antiparticle pair can pop out of empty space ("the vacuum") and then vanish back into it

These are *Virtual* particles.



Vacuum Fluctuation
Involving top quarks

Other examples of Virtual particles:



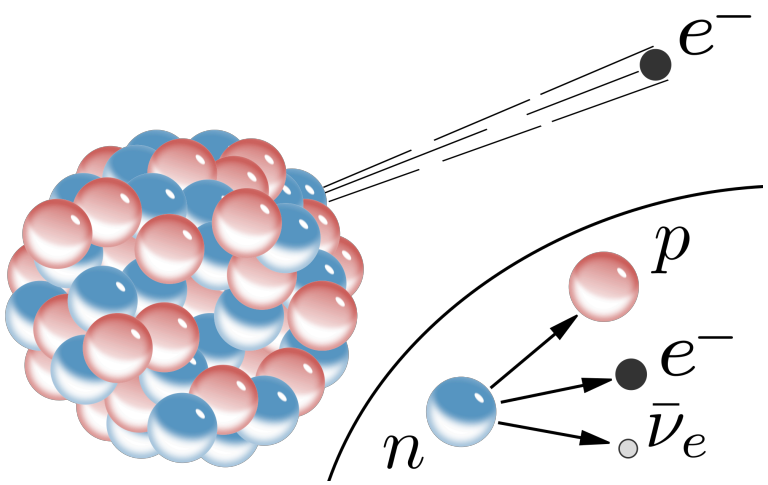
This has far-reaching consequences

- The structure of the universe depends on particles that ***don't exist in the usual sense***
- We do not see these particles in everyday life
- We must recreate the state of the early hot universe to make them

Beta decay revisited

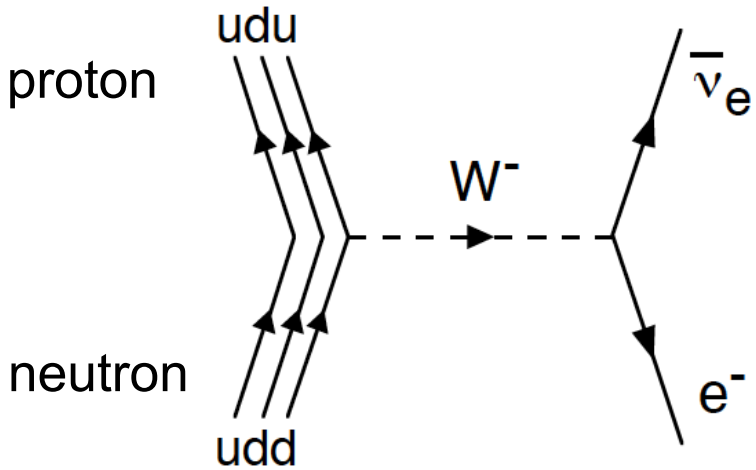
Fermi theory (1930-35):

the neuron decays in a proton, electron and neutrino



Standard Model (1960-65):

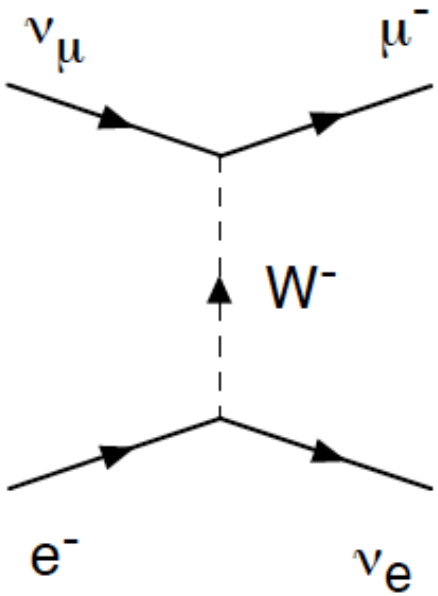
a quark d in the neutron emits a W^- and is transformed into a u quark; the W^- decays in a electron and a anti-neutrino



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



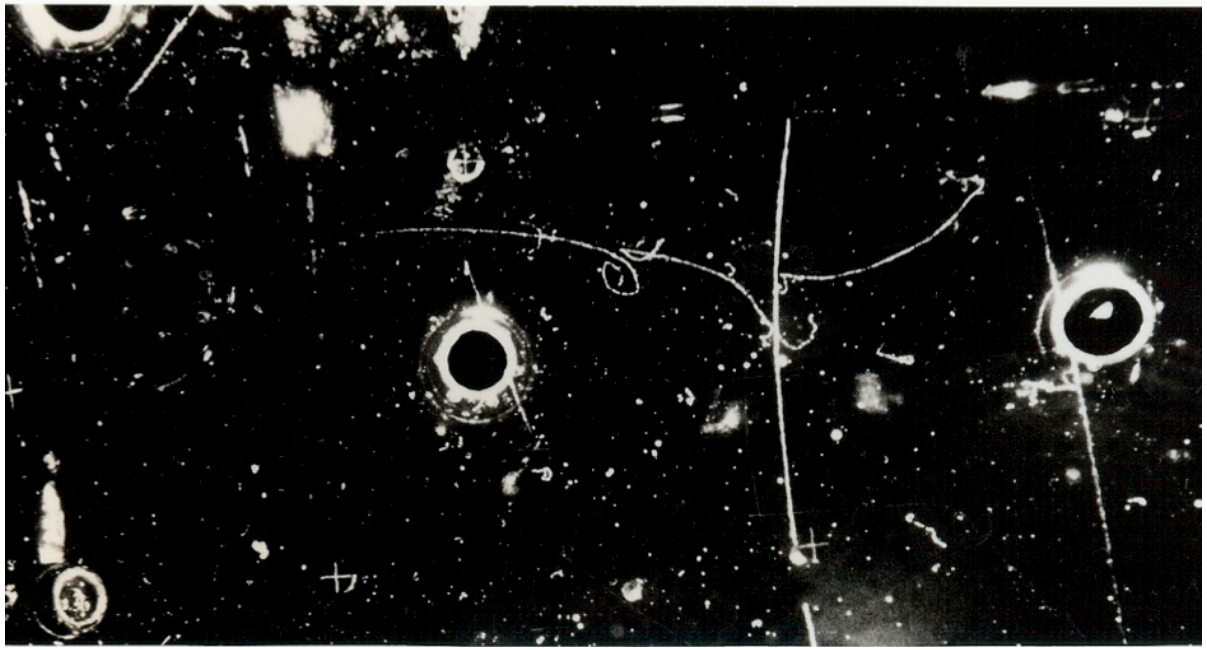
"Charged current" neutrino interaction

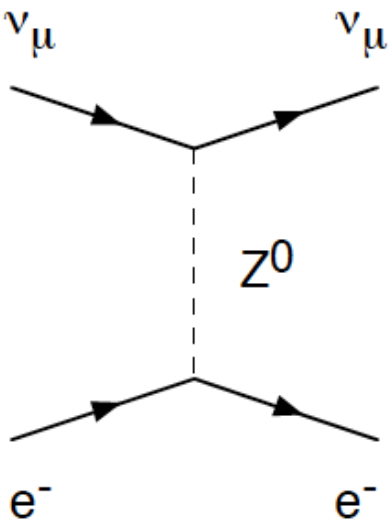
W boson is exchanged

Discovery of neutral currents

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

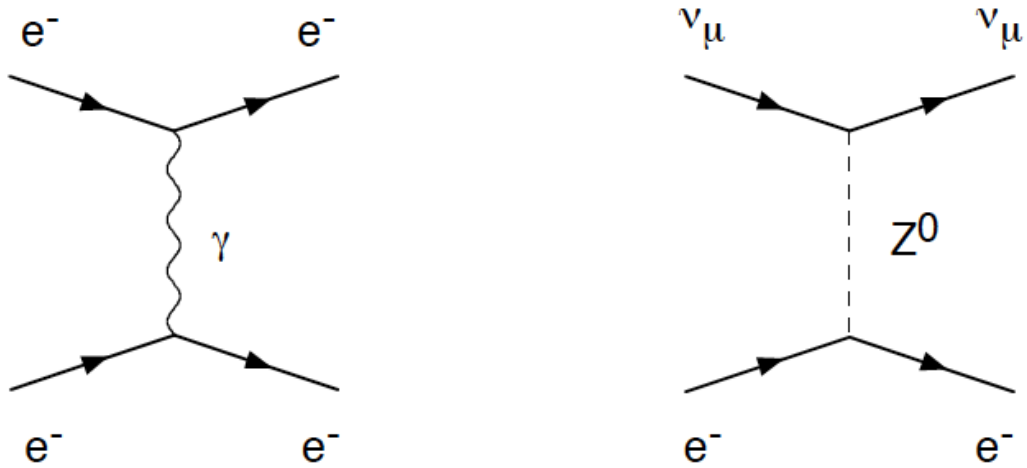
First observation of events $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$





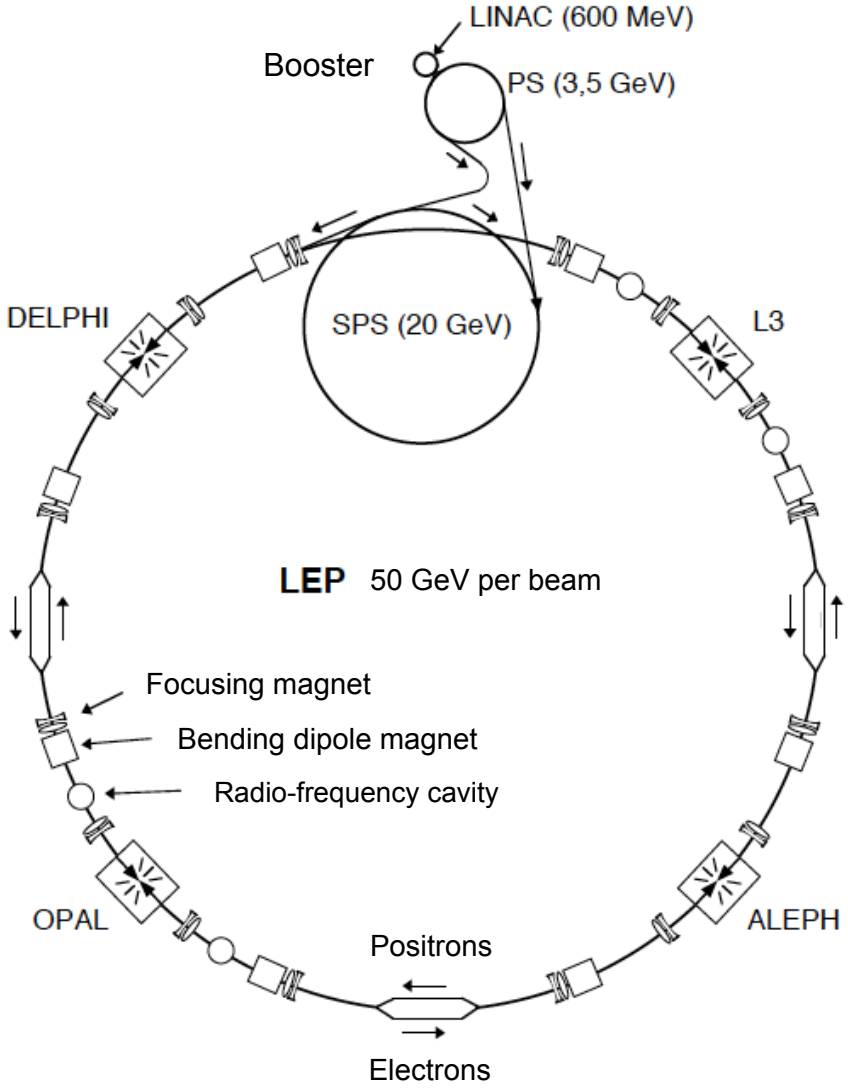
Weinberg-Salam model

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:

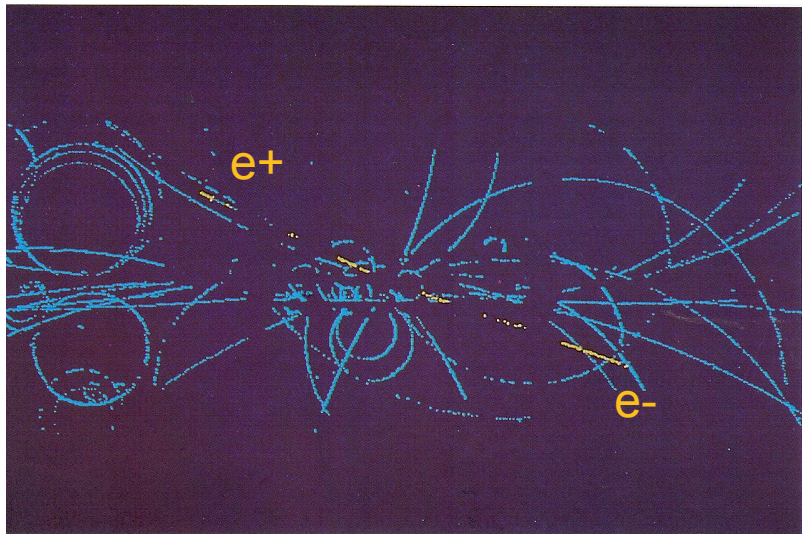
- Beam-Target:
  $\sqrt{s} = E_{CM} = \sqrt{2.E_{beam}.m}$
- Beam-Beam:
  $\sqrt{s} = E_{CM} = 2.E_{beam}$

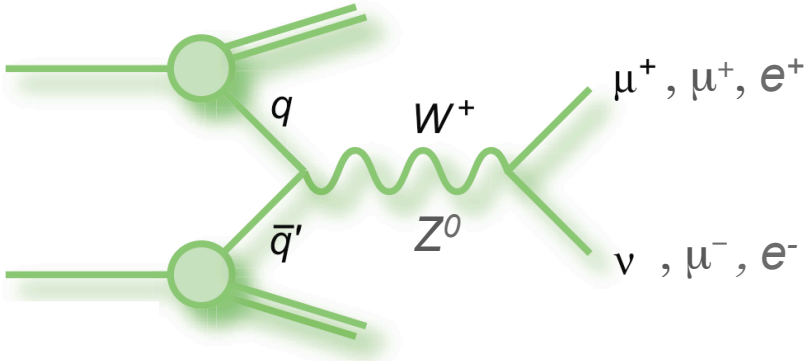
Discovery of W and Z bosons

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

C. Rubbia, future Nobel laureate, 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





The hunt for the top quark

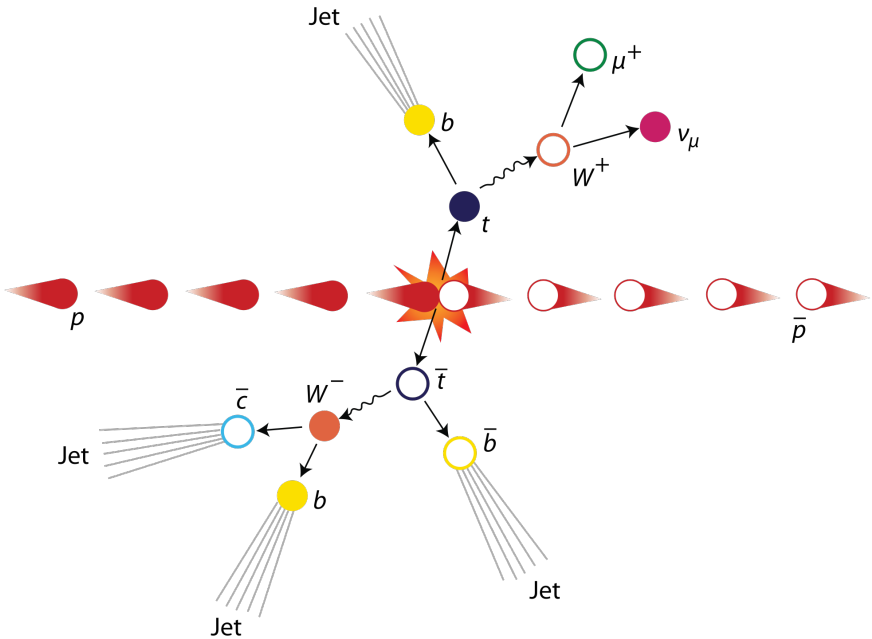
The hunt started at SLAC (Stanford) and DESY (Hamburg), continued at CERN with higher energy beams (SppS and later on LEP) and moved to Fermilab in 1988 when the new accelerator giving 900 GeV protons and antiprotons became operational.

A top and anti-top quark pair is produced.

The top quark decays into W and b-quark.

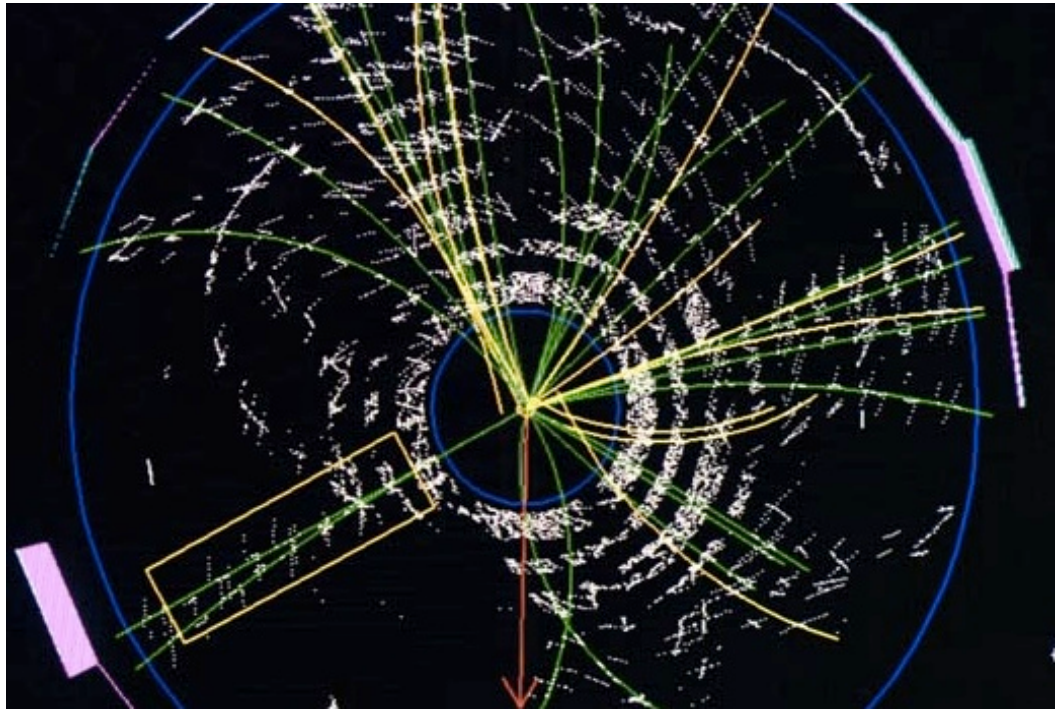
W can decay into a pair of leptons (for example, electron + electron neutrino) or a pair of quarks (pair of jets).

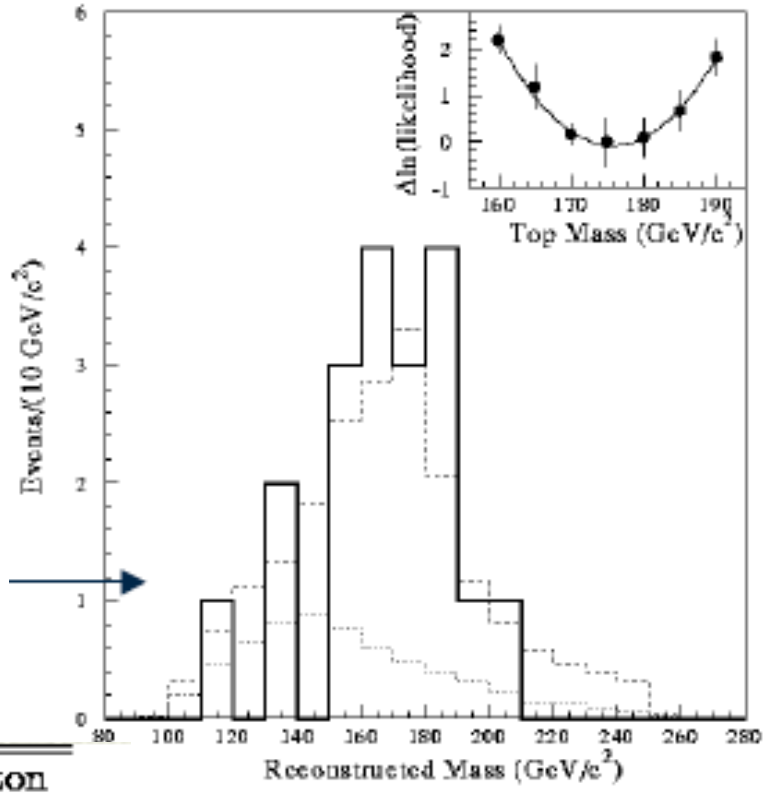
The b-quarks will give jets.



Top quark discovery

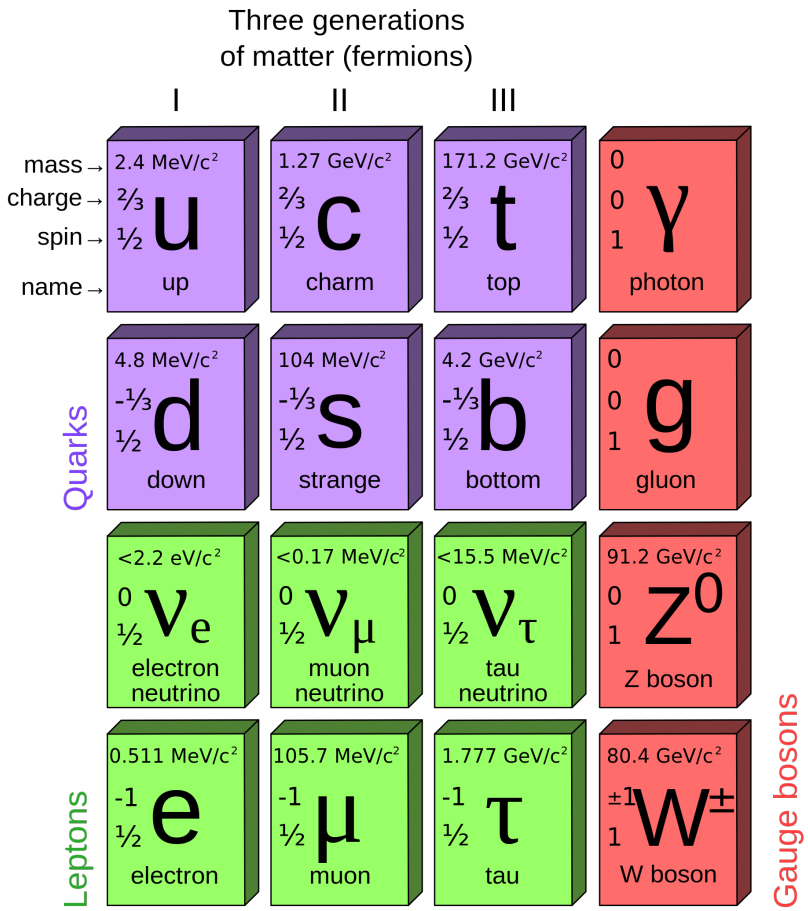
Top quarks were seen for the first time in 1995 at Fermilab near Chicago



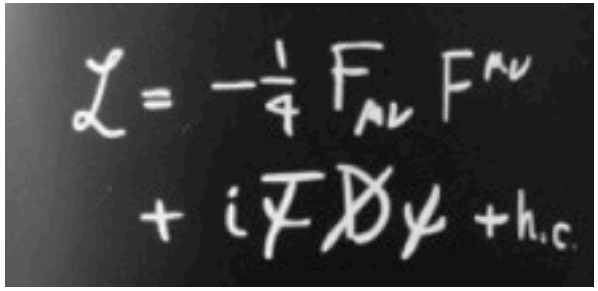


Channel:	SVX	SLT	Dilepton
observed	27 tags	23 tags	6 events
expected background	6.7 ± 2.1	15.4 ± 2.0	1.3 ± 0.3
background probability	2×10^{-5}	6×10^{-2}	3×10^{-3}

Putting all together



STANDARD MODEL OF ELEMENTARY PARTICLES



What's missing?

A "funny" thing happened on the way to the modern theory of quarks, leptons, force fields, and their quanta:

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

End of Lecture 1