FROM ELECTRONS TO QUARKS

The development of Particle Physics

QUARKNET 2001, FSU
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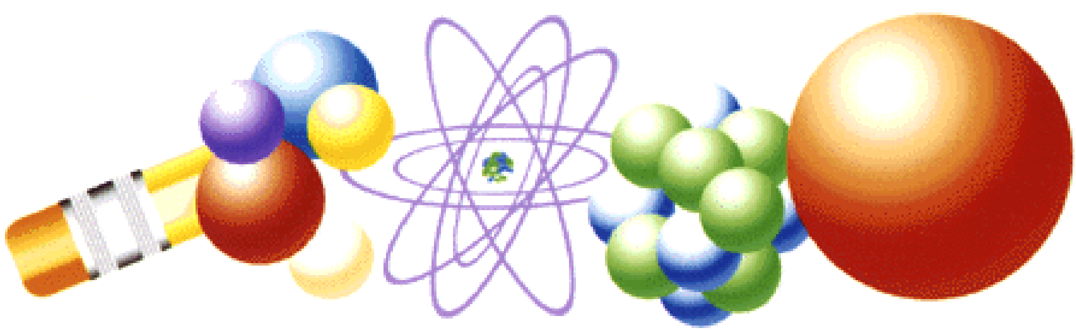


Outline

- What is Particle Physics?

- The origins of Particle Physics: the atom (p,e^-), radioactivity, and the discovery of the neutron (n). (1895-1932)

- Cosmic Rays: the positron (e^+), the muon ($\mu^\pm$), the pion ($\pi^\pm, \pi^0$), and the Kaon ($K^\pm, K^0$). (1932-1959)

- Colliders: more and more particles discovered, patterns emerge (1960's and on):
$\rightarrow$ leptons and hadrons
$\rightarrow$ electromagnetic, weak, and strong interactions

- the Quark Model of hadrons and QCD: strong interactions

- The Standard Model of Electroweak interactions

- Open Problems

- Beyond the Standard Model

What is Particle Physics?

it is explaining the physical world, from the smallest atomic scale to the astronomical scales, in terms of the same

$\rightarrow$ fundamental constituents of matter ("building blocks")

$\rightarrow$ fundamental forces between them ("interactions").

$$\Downarrow$$

- Are there irreducible building blocks?

$\rightarrow$ how many?

$\rightarrow$ properties? (mass, charge, flavor, ...)

- How do they interact?

$\rightarrow$ how many forces?

$\rightarrow$ differences/similarities?

- What is mass?

- What is charge?

...

The Origins of Particle Physics

In school text books we learn that

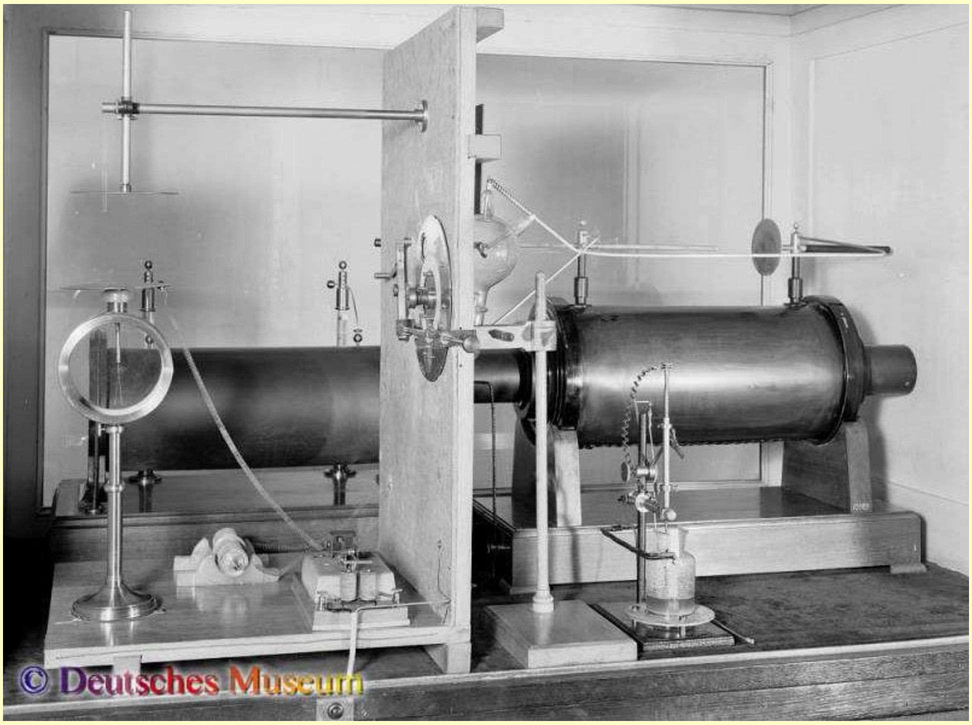
• All matter is composed of atoms, which themselves form aggregates called molecules.
• An atom contains a nucleus of positive charge $+Z$ and Z electrons.
• If the atomic mass is A, the nucleus contains Z protons and $A - Z$ neutrons.

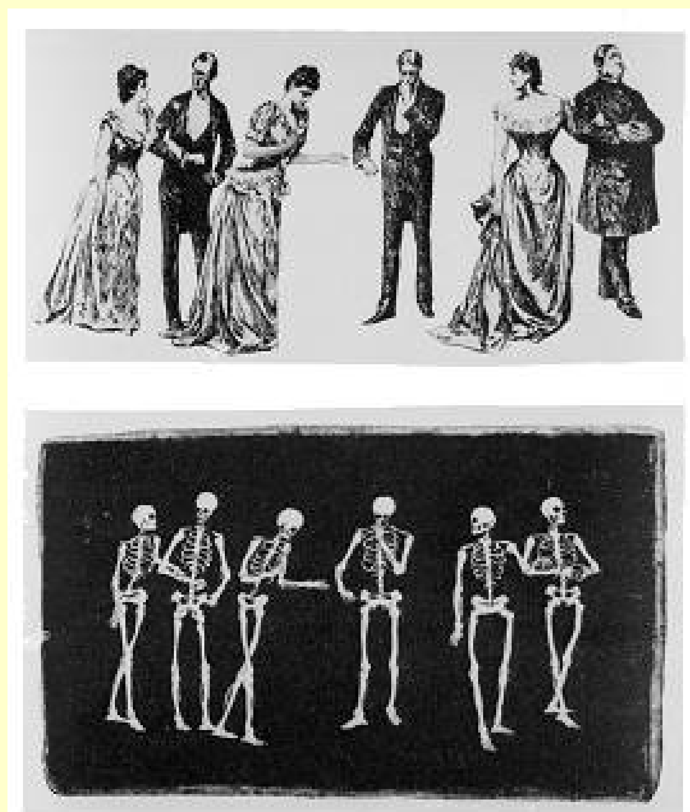
This picture did not exist in 1895 . . .

• atoms creation of chemists
• electron, proton and neutron were yet to be discovered
• atomic spectra were known but not understood
• "*cathode rays*" discovered: look like particles with negative charge.

. . . when Röntgen discovers x-rays!

- Röntgen and X-rays:





Hand of Anna Röntgen

From Life magazine,6 April 1896

• 1896-97 : "*cathode rays*" are negatively charged particles of charge e and mass m, s.t. e/m is 2000 times larger than H

$$\Downarrow$$

Thomson's Model of the atom

• 1896-1900: enormous effort in study of radioactive elements (Becquerel, Curie's, Rutherford)

• 1906-1911: Geiger, Marsden and Rutherford's scattering experiments

$$\Downarrow$$

Rutherford's Model of the atom

But:

$\rightarrow$ electron orbiting around the nucleus accelerates and therefore (Maxwell) radiates
$\rightarrow$ electron looses energy by radiation: orbit decays
$\rightarrow$ continuum spectrum and unstable atoms.

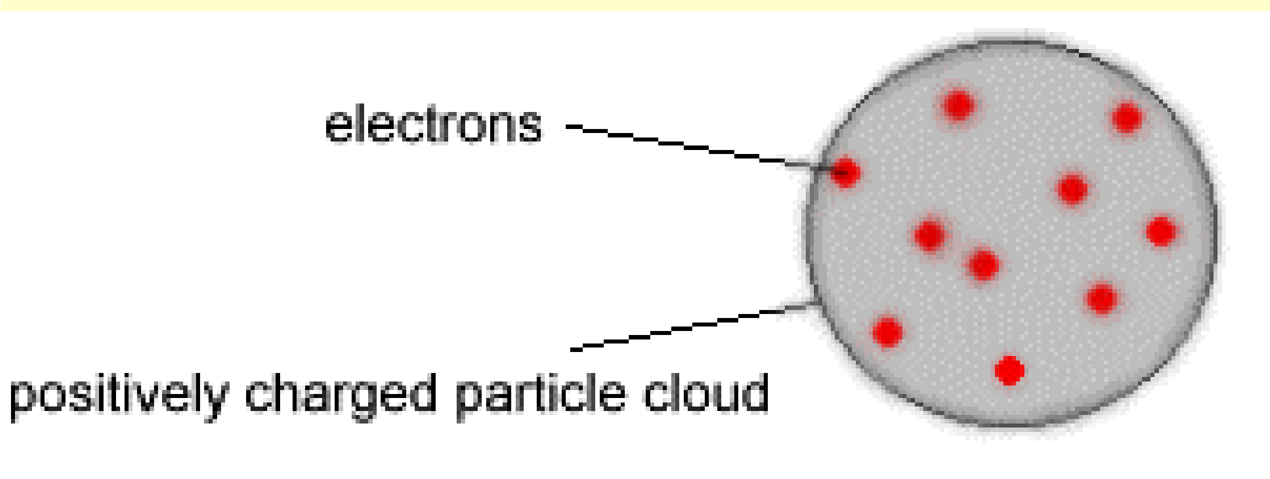
Answers:

1924-1927 Quantum Mechanics

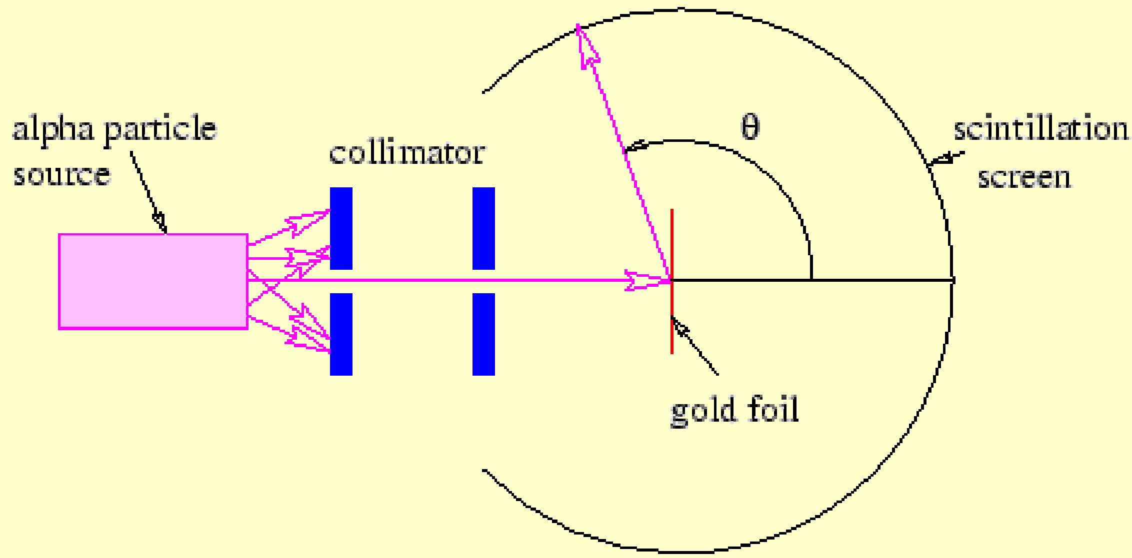
(Planck,Bohr,De Broglie,Heisenberg,Schrödinger,Dirac,...)

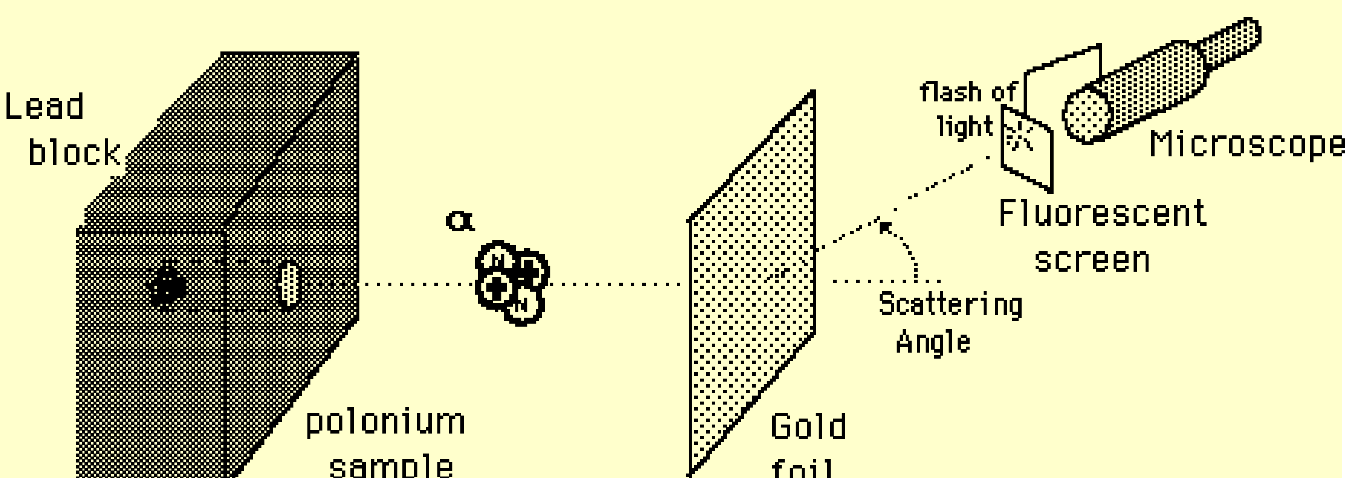
WHAT IS INSIDE AN ATOM?

- J.J. Thomson's model:
  - "Plum pudding or raisin cake model"
    - atom = sphere of positive charge (diameter $\approx 10^{-10}$ m),
    - with electrons embedded in it, evenly distributed (like raisins in cake)
    - i.e. electrons are part of atom, can be kicked out of it – atom no more indivisible!



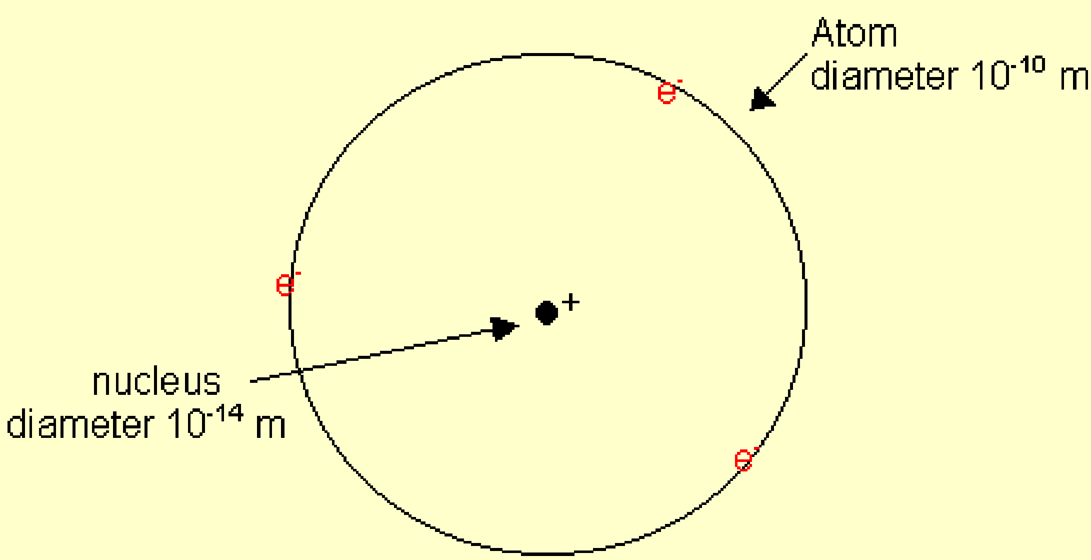
Geiger, Marsden, Rutherford expt.



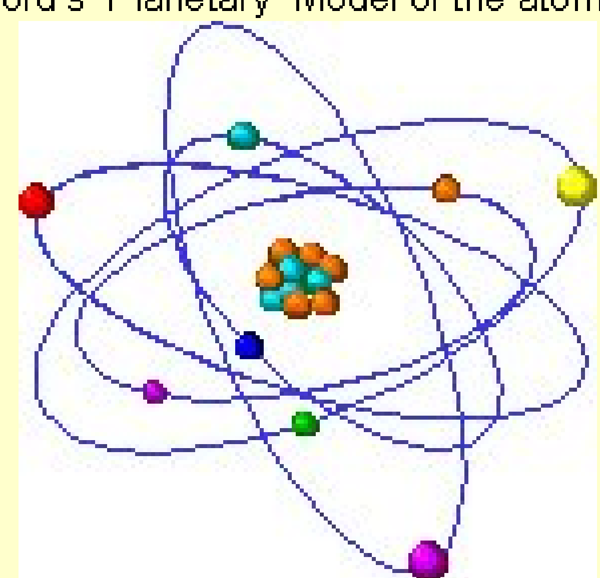


Rutherford model

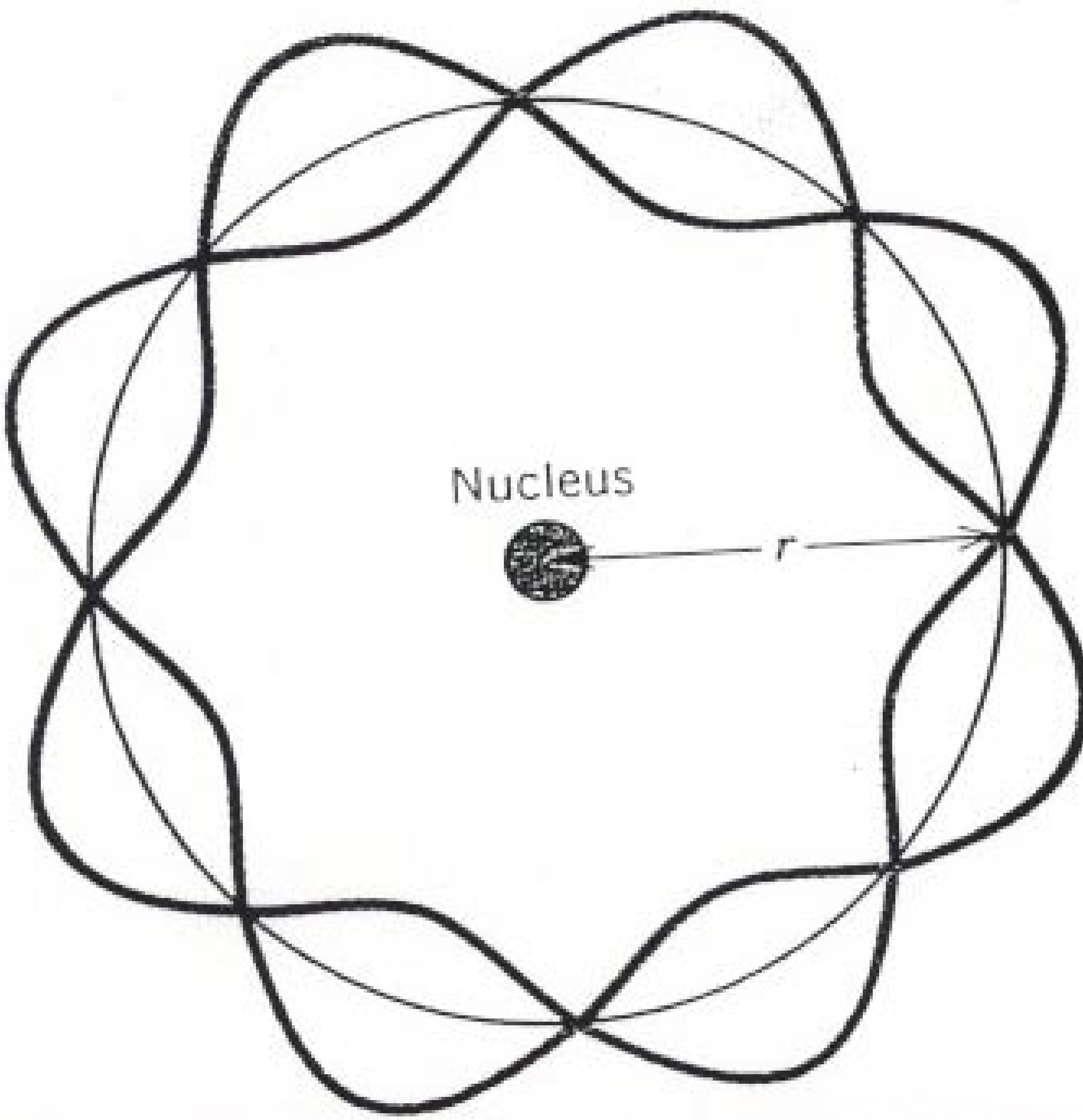
- RUTHERFORD MODEL OF ATOM:
  ("planetary model of atom")
  - positive charge concentrated in nucleus ($<10^{-14}$ m);
  - negative electrons in orbit around nucleus at distance $\approx 10^{-10}$ m;
  - electrons bound to nucleus by Coulomb force.



Rutherford's "Planetary" Model of the atom



De Broglie, Bohr model



- 1932 : Chadwick discovers the neutron

$$He_2^4 + Be_4^9 \rightarrow C_6^{12} + n_0^1$$

$$\Downarrow$$

The modern atom is complete

However ... Most is still to come!

The Development of Particle Physics

- Evidence of very light neutral particle in β decay: the electron neutrino (predicted by Pauli in 1930, discovered by Cowan and Reines in 1956-58)

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

- Cosmic Rays: atmospheric nuclear collision of incoming high energy protons produce new particles

$\to$ 1932: positron (e^+) (Anderson), as predicted by Dirac (1928)

$\to$ 1936-1951: the muon ($\mu^\pm$) and the pion ($\pi^\pm, \pi^0$)

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^0 \to \gamma\gamma$$

$\to$ 1943-1959: the discovery of "*strange particles*", the Kaon ($K^\pm, K^0, \bar{K}^0$)

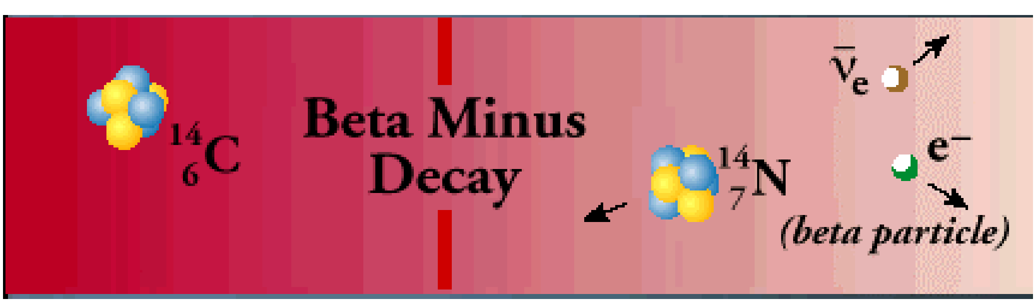
$$K^0 \to \pi^+ + \pi^-$$

$$K^+ \to \mu^+ + \nu_\mu \quad \cdots$$

Beta decay

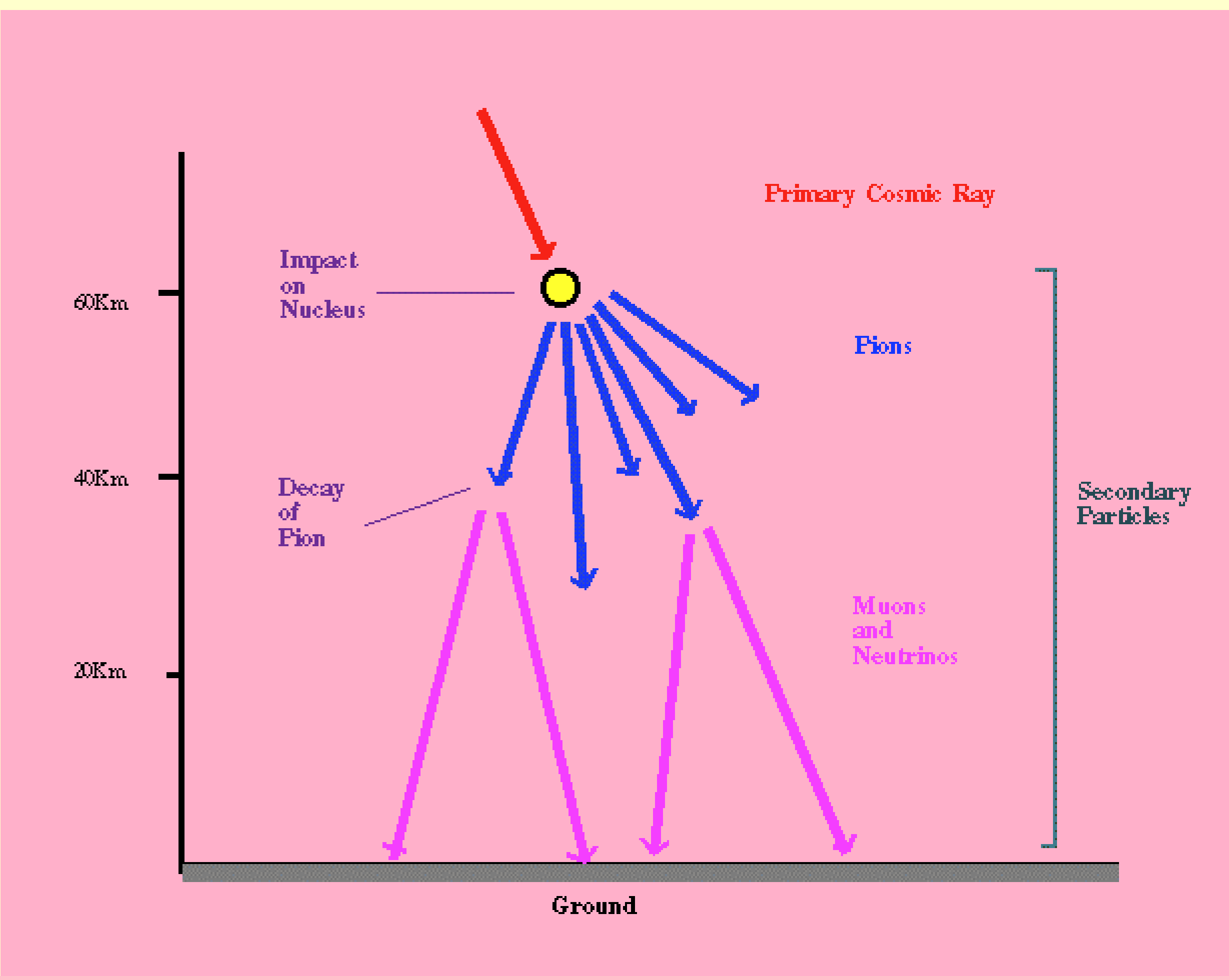
β decay $\quad n \rightarrow p + e^- + \bar{\nu}_e$

- β decay changes a neutron into a proton
- Only observed the electron and the recoiling nucleus
  - "non-conservation" of energy
- Pauli predicted a light, neutral, feebly interacting particle (1930)
  - the neutrino
- Although accepted since it "fit" so well, not actually observed initiating interactions until 1956-1958 (Cowan and Reines)



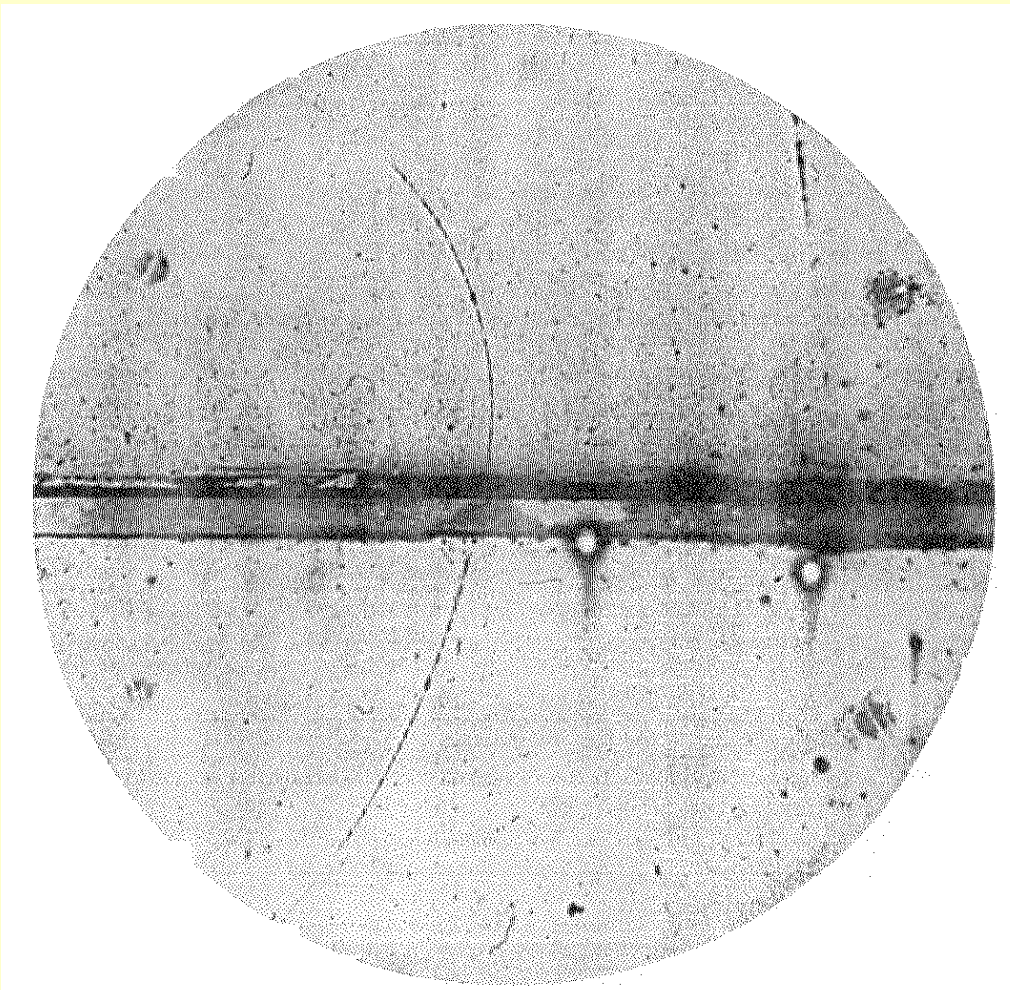
Cosmic rays

- Discovered by Victor Hess (1912)
- Observations on mountains and in balloon: intensity of cosmic radiation increases with height above surface of Earth – must come from "outer space"
- Much of cosmic radiation from sun (rather low energy protons)
- Very high energy radiation from outside solar system, but probably from within galaxy



Positron

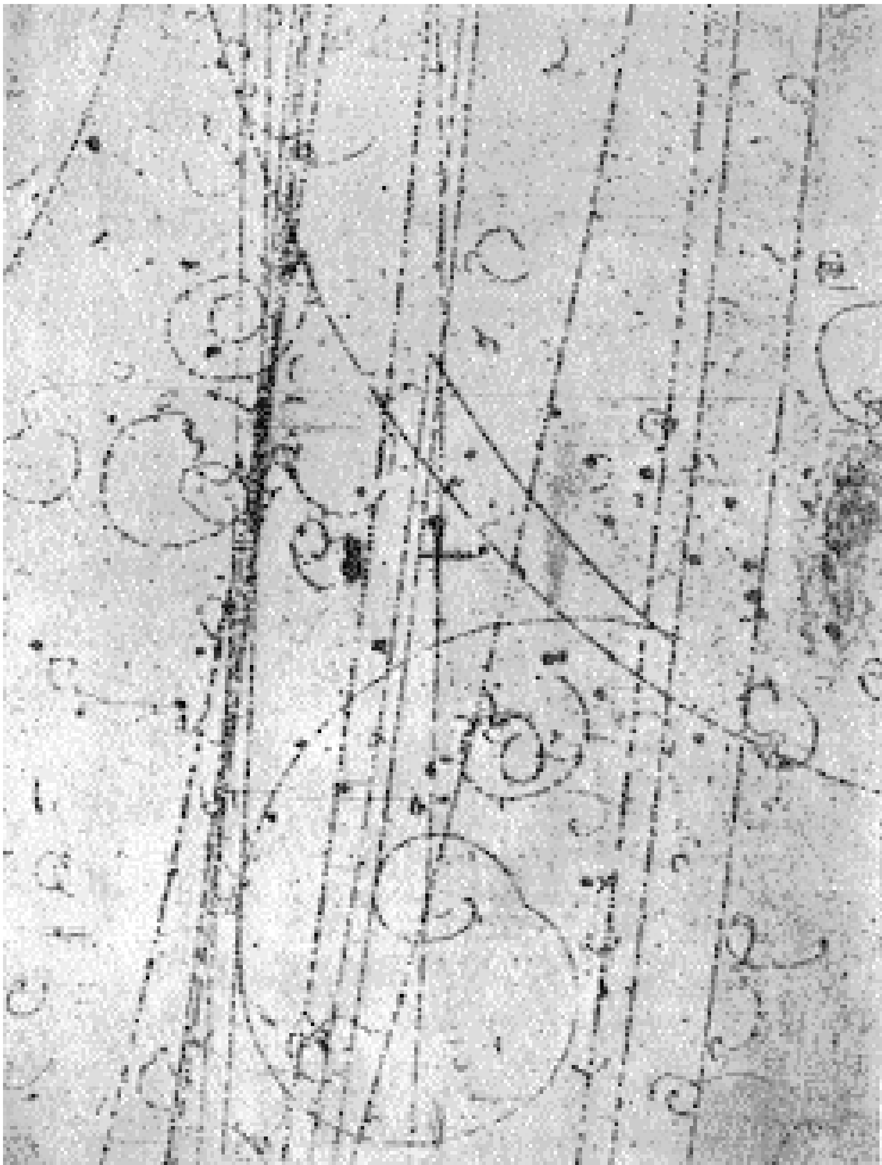
- Positron (anti-electron)
  - Predicted by Dirac (1928) -- needed for relativistic quantum mechanics
  - existence of antiparticles doubled the number of known particles!!!

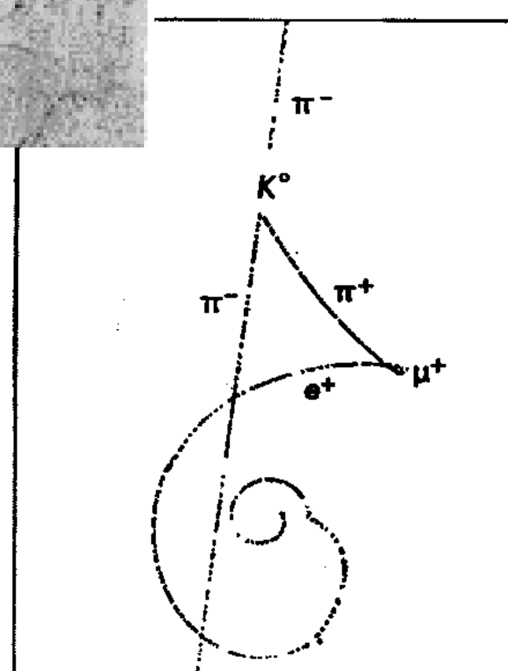


  - Positron track going upward through lead plate
    - Photographed by Carl Anderson (August 2, 1932), while photographing cosmic-ray tracks in a cloud chamber
    - particle moving upward, as determined by the increase in curvature of the top half of the track after it passed through the lead plate,
    - and curving to the left, meaning its charge is positive.

"Strange particles"

- Kaon: discovered 1947; first called "V" particles





K^0 production and decay
in a bubble chamber

1940's → 1950's

A plethora of particles is discovered

(mainly in cosmic rays)

e^-, p, n, ν_e, μ^-, $(\pi^\pm, \pi^0)$, e^+

plus

$(K^\pm,\ K^0,\ \bar{K}^0)$, Λ^0, $\bar{p}$, (Σ^+, Σ^0), Ξ, ...

NATURE CANNOT BE SO MESSY!

⇓

- Are all these particle intrinsically different?

OR

- Can we recognize patterns or symmetries in their nature (charge,mass,flavor) or the way they behave (decays)?

1950's → .....
A new era for particle physics

We can convert energy into particles

$$E^2 = p^2c^2 + m^2c^4$$

and reproduce the primordial stages of our universe (almost...)

⇓

Collider Physics

$$e^+e^- \ , \ p\bar{p} \ , \ \ldots.$$

With High Energies we can:

→ make objects of large mass
→ resolve structure at small distances

First Great Discoveries....

• $e^{\pm}, \mu^{\pm}, \tau^{\pm}$ and their neutrinos (we call them *Leptons*) are fundamental particles and interact electromagnetically and "*weakly*"

while

• p, n, $(\pi^{\pm}, \pi^0)$, $(K^{\pm}$, K^0, $\bar{K}^0)$, Λ^0, (Σ^+, Σ^0), Ξ, ... (we call them *Hadrons*) are not fundamental particles!

$\Downarrow$

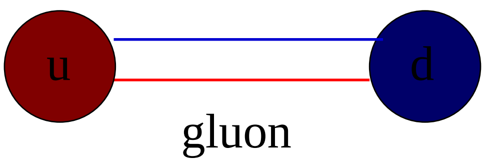
They are made of QUARKS!
named up, down, and strange

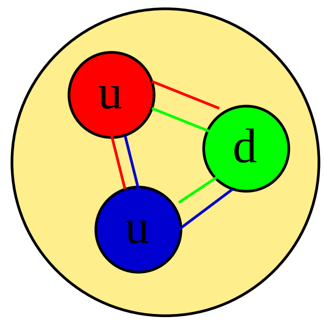
and they interact electromagnetically, "*weakly*", and "*strongly*".

Quarks carry a COLOR charge

un UP quark can be $\left\{ \begin{array}{ll} up & (green) \\ up & (red) \\ up & (blue) \end{array} \right.$

and interact exchanging GLUONS, the carriers of the STRONG FORCE





Barions	Mesons
(qqq)	$(\bar{q}q)$
$p \rightarrow uud$	$\pi^{\pm} \rightarrow u\bar{d}(\bar{u}d)$
$n \rightarrow ddu$	$\pi^0 \rightarrow u\bar{u} + d\bar{d}$
$\Sigma^+ \rightarrow uus$	$K^{\pm} \rightarrow u\bar{s}(\bar{u}s)$
$\Sigma^0, \Lambda^0 \rightarrow uds$	$K^0(\bar{K}^0) \rightarrow \bar{s}d(s\bar{d})$
$\Xi^0 \rightarrow uss$	$\rho \rightarrow u\bar{d}$
$\ldots$	$\ldots$

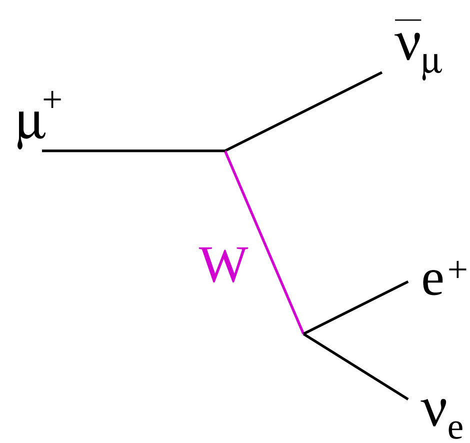
Both Leptons and Quarks carry a Weak Charge

as well as the usual electric charge

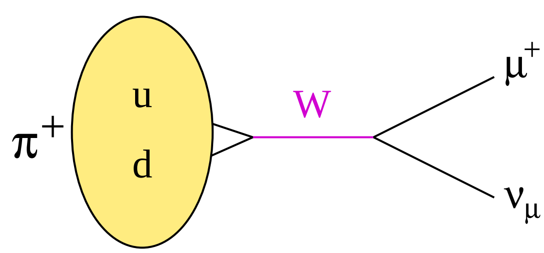
and also interact exchanging:

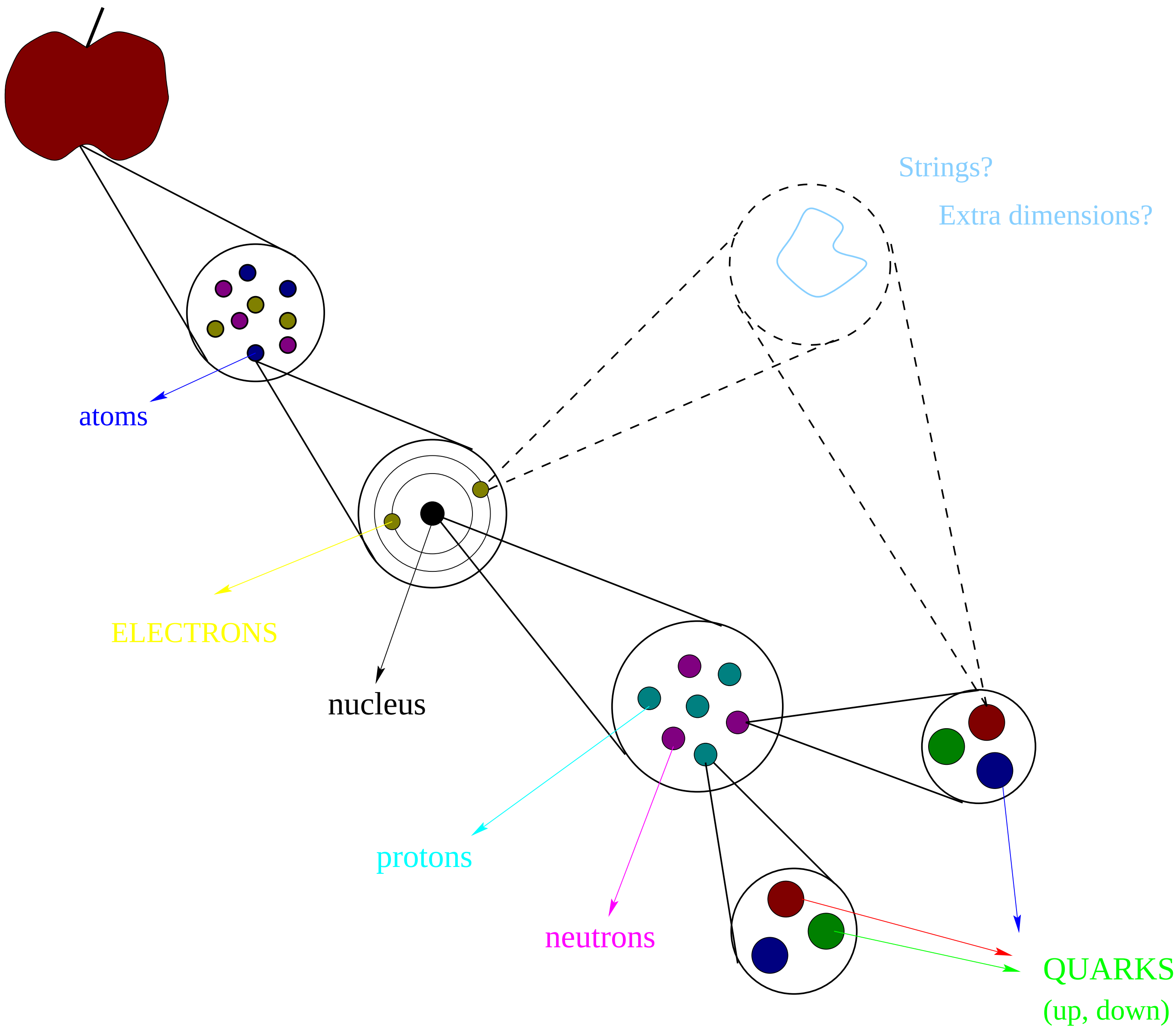
- Neutral EW force carriers : γ (photon), Z^0 ($M_\gamma = 0, M_Z = 91$ GeV)
- Charged EW force carriers : $W^\pm$ ($M_W = 80$ GeV)

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$





Strings?
Extra dimensions?
atoms
ELECTRONS
nucleus
protons
neutrons
QUARKS
(up, down)

Some Milestones...

→ Quantum Electrodynamics (QED) (1950's), (Feynman,Schwinger,Tomonaga)

→ Electroweak unification: the Standard Model (1960's) (Glashow,Weinberg,Salam)

→ SLAC/MIT elastic/inelastic scattering from nucleons (1956-1973)

→ Quark Model (1964) (Gell-Mann,Zweig)

→ Quantum Chromodynamics (QCD) (1970's) (Gross, Wilceck, Politzer,...)

More Quarks coming along .....

1974 $\rightarrow$ Discovery of the charm quark ($\psi = c\bar{c}$, D mesons) (BNL, SLAC)

1977 $\rightarrow$ Discovery of the bottom quark ($Y = b\bar{b}$, B mesons) (FERMILAB, DESY)

1995 $\rightarrow$ Discovery of the top quark (no bound state) (FERMILAB)

And more Forces .....

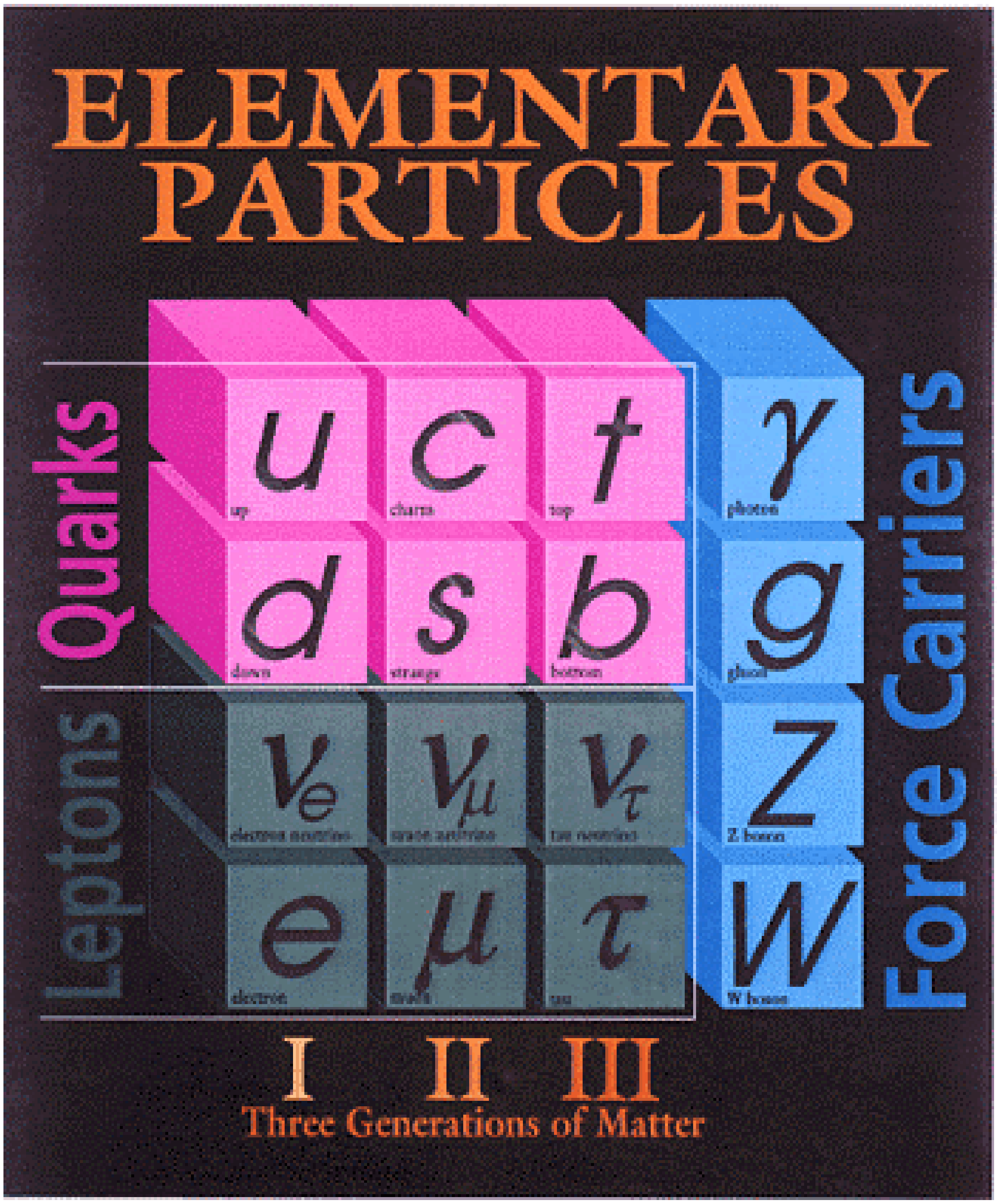
1983 $\rightarrow$ Discovery of the $W^{\pm}$ and Z bosons, carriers of the WEAK FORCE (CERN)

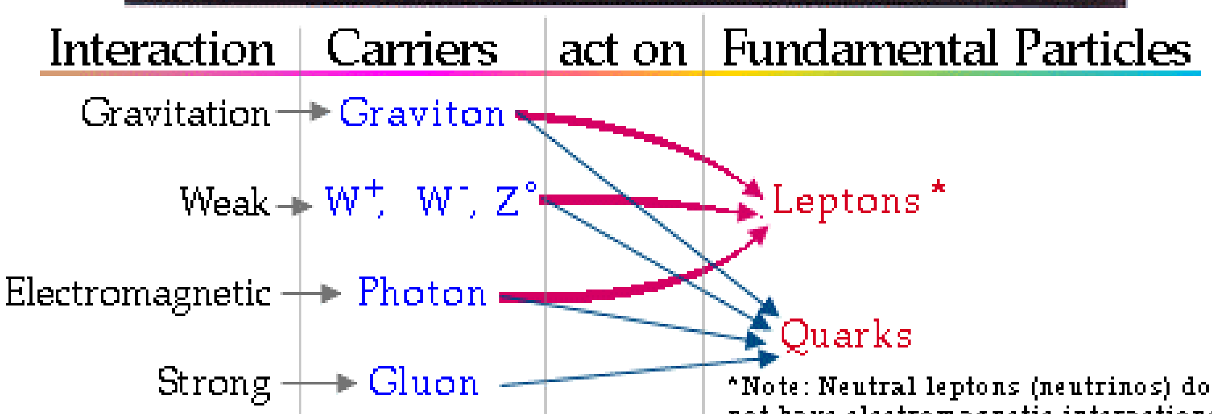
$\Downarrow$

As the Standard Model predicts

1990's $\rightarrow$ Precision tests of the Standard Model (CERN,SLAC,FERMILAB)

Standard Model





Open Problems .....

- What is the origin of mass??

$\Downarrow$

the Higgs boson

a very elusive particle.....

$\rightarrow$ no direct evidence yet
$\rightarrow$ many indirect pieces of evidence

- Do forces unify??

- Are there more fundamental objects than just leptons and quarks??

- Are there extra dimensions?? i.e. are four dimensions enough??

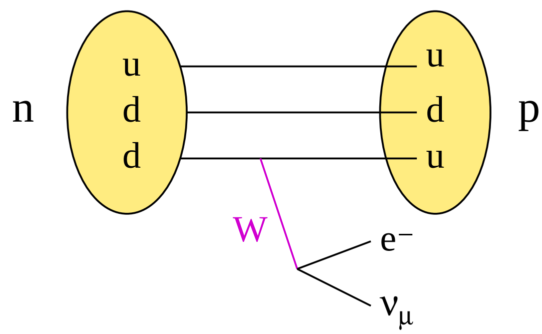
Direct vs Indirect Evidence

- Either you produce a new particle: Direct Evidence or Discovery

- Or you see it in a "virtual state": Indirect Evidence

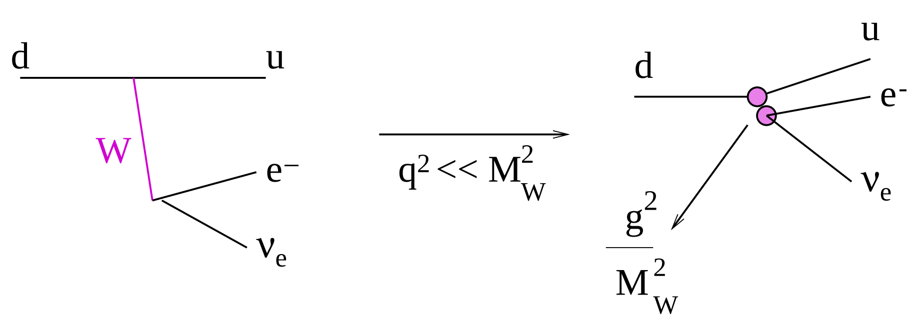
  Very famous example: β decay

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



Fermi's Theory: pointlike interaction

$$\text{decay rate} \propto G = \frac{g^2}{M_W^2}$$



Why all these particles and forces??

Who ordered it? (Rabi)

- Most of the particle the world is made of are : electrons, protons, and neutrons (e^+, u, and d quarks).

- This is because our world lives at very low energy.

- All other particles were created at the high energies of the very early stages of our universe and we can nowadays recreate some of them in our laboratories, even if for very short time

$\rightarrow$ Tevatron ($p\bar{p}$), Fermilab (Chicago) (2001)

$\rightarrow$ B-factories (SLAC, KEK) (e^+e^-)(1999)

$\rightarrow$ LHC (pp), CERN (Geneva, CH) ($\sim$ 2006)

$\rightarrow$ NLC/Tesla (e^+e^-) ($\sim$ 2020?)

We may have to look back at the universe to know more and try to unify the very large with the very small!