

Kinetic theory,
Thermodynamics

Boltzmann

Maxwell

Newton

Particles

Fields

Universe

Technologies

1895

1900

1905

1910

1920

1930

1940

1950

1960

1970

1975

1980

1990

2000

2010

e^-

Brownian
motion

Photon

Radio-
activity

3

4

Atom

Special
relativity

Nucleus

Quantum mechanics
Wave / particle
Fermions / Bosons

p^+

n

Dirac

Antimatter

Fermi Beta-
Decay

Yukawa
 π
exchange

Cosmic
rays

General
relativity

Geiger

Cloud

Galaxies; expanding
universe

Cyclotron

Dark Matter

Nuclear fusion

Big Bang
Nucleosynthesi
s

Synchrotron

μ^-

π

QED

P, C, CP
violation

τ^-

p^-

Particle
zoo

ν_e

W bosons

Cosmic Microwave
Background

e^+e^- collider

ν_μ

u d s

Higgs

EW unification

Wire chamber

Beam cooling

ν_τ

c

GUT

QCD
Colour

Online computers

τ^-

STANDARD MODEL

SUSY

Inflation

p^+p^- collider

ν_τ

b

Superstrings

W

Z

g

Modern
detectors

1990

2000

2010

ν mass

t

3 generations

CMB Inhomogeneities
(COBE, WMAP)

Dark Energy (?)

WWW

GRID

Back to the beginning of the century - another interaction was being discovered

The “Weak Interaction”

1895: Wilhelm Röntgen discovered 'X-rays'

1896: Henri Becquerel discovered radiation from U crystals

1898: Marie and Pierre Curie : ionizing radiation from 'Pechblende' (U + Polonium)

Radioactivity

It took 35 years to understand what was going on ...

Fields

'Weak' interaction

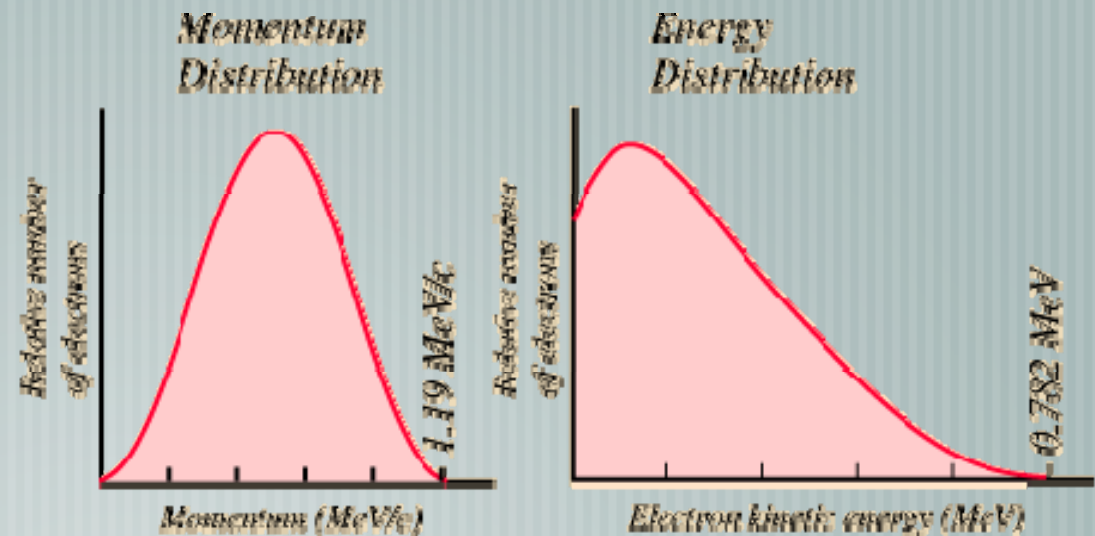
Beta decay of nuclei - electrons emitted with continuous energy spectrum !?

$$Z \rightarrow (Z+1) + e^- ?$$



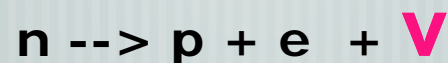
1911 Lise Meitner, Otto Hahn

Violation of energy conservation?



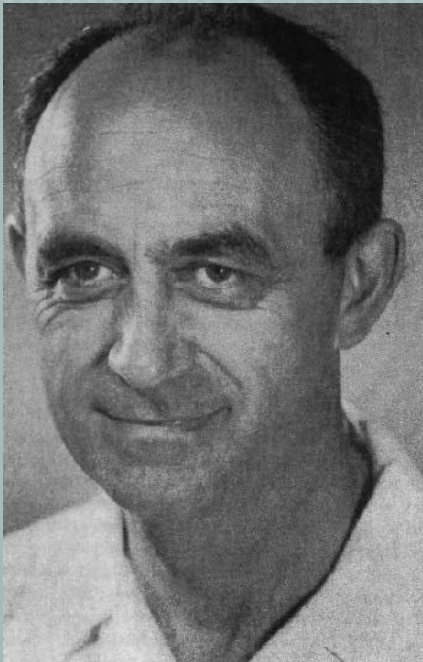
1930 Wolfgang Pauli: an **extremely light neutral particle*** is emitted in beta decay

*'neutron', but in 1931 Fermi called it "neutrino" (little neutron)

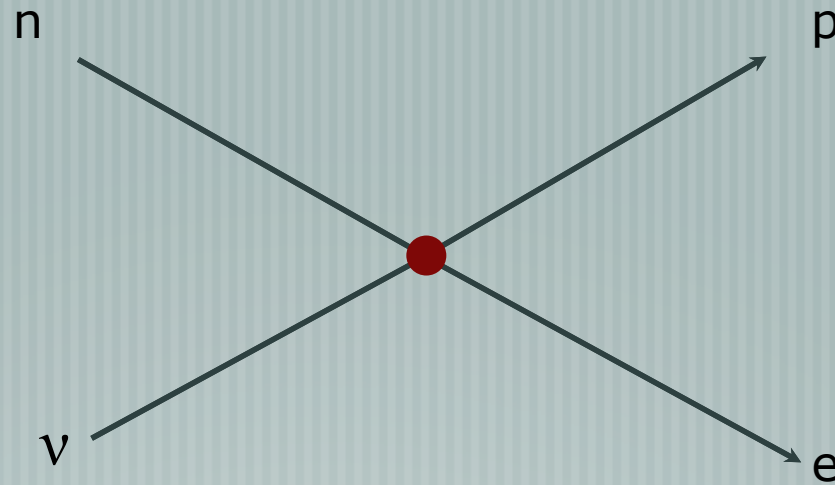


Fields

'Weak' interaction



Enrico Fermi
(1934)



Proposed a phenomenological model of weak interaction

Point-like coupling with strength $G_F \sim 10^{-5}$ of e.m. interaction

Coupling of two 'currents' (proton-neutron / electron-neutrino)

Ok until ~1960

Fields

'Strong' interaction

What keeps the protons and neutrons together in the nucleus?

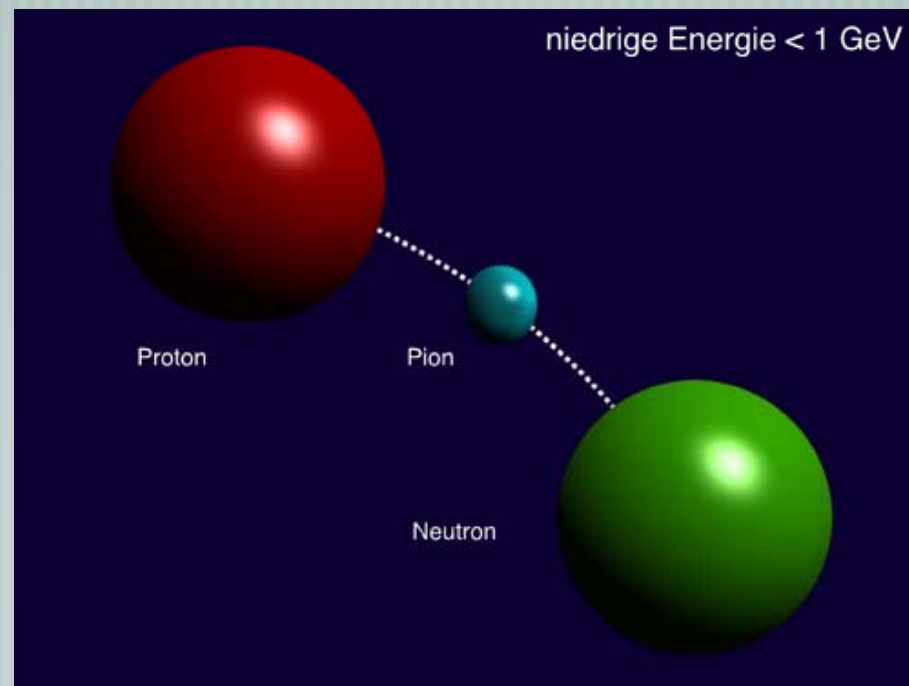


Yukawa (1934)

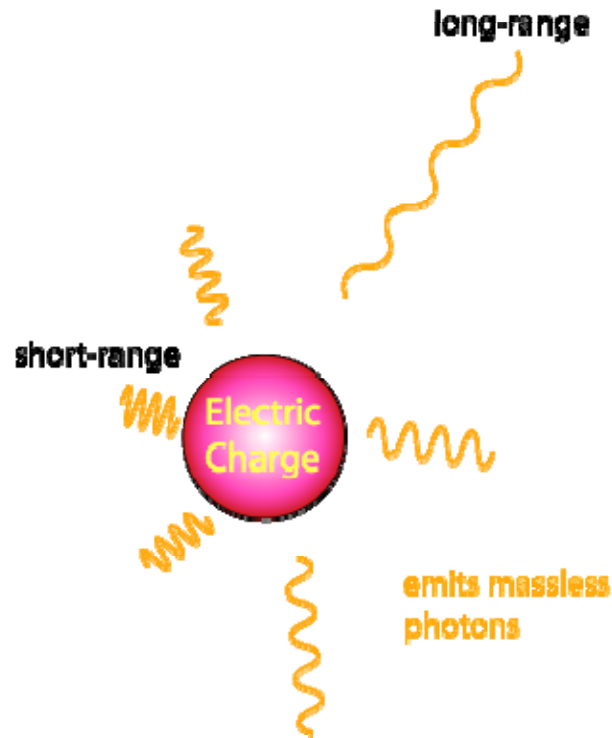
- 1) This force must be stronger than the electromagnetic repulsion
- 2) It must be of short range ($\sim 1\text{-}2\text{ fm}$) to explain the size of nuclei

Yukawa's idea:

a massive particle ("pion") is exchanged between two nucleons

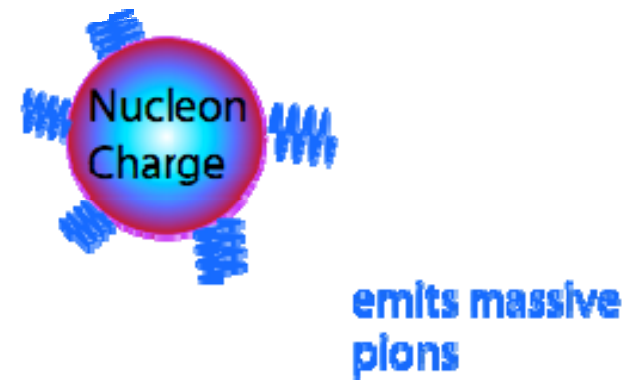


Electromagnetic vs Nuclear



$$V(r) = -e^2 \frac{1}{r}$$

Coulomb law

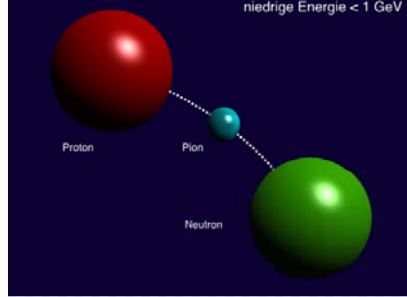


$$\Delta E \Delta t \geq \hbar \quad (\Delta E \sim m)$$

$$r = c \Delta t = \frac{\hbar c}{m} \sim \frac{200 \text{ MeV fm}}{m}$$

$$V(r) = -g^2 \frac{e^{-mr}}{r}$$

Yukawa potential ~ Modified "Coulomb" law



Fields

'Strong' interaction

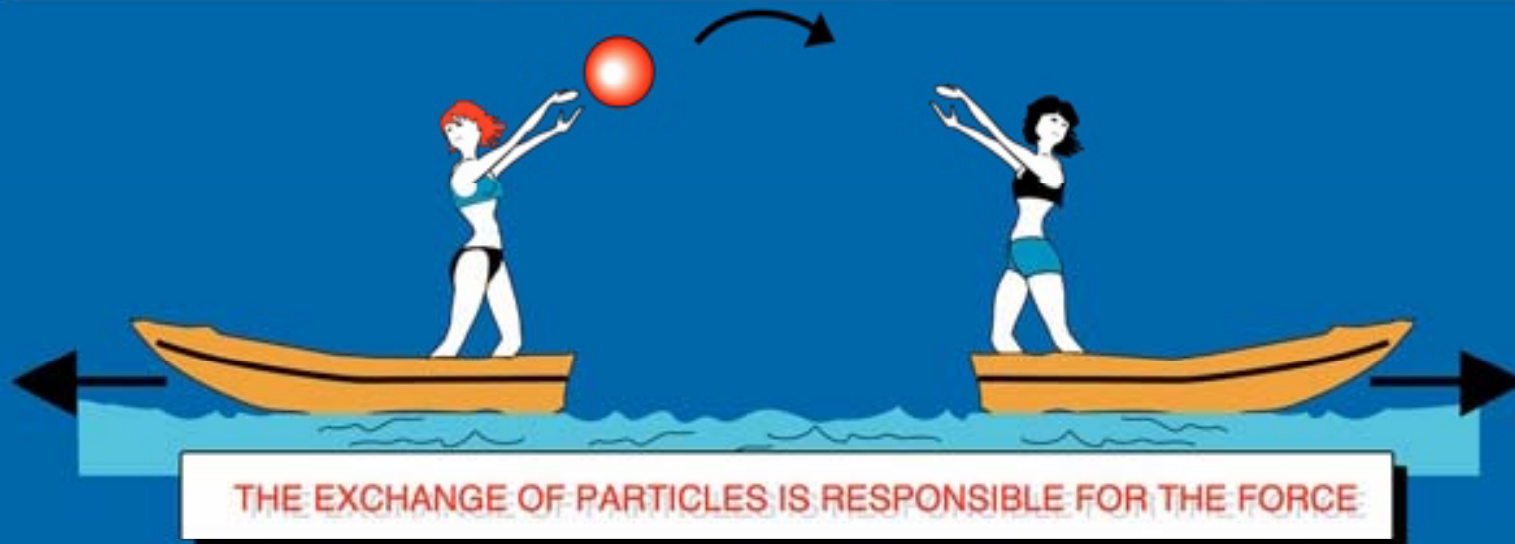
Metaphors for 'particle exchange'



Allowed by uncertainty relation: $1.4 \text{ fm} \sim 140 \text{ MeV}$

The forces in Nature

TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	$\sim 10^{-3}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^0, W^+, W^- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES



4

The Universe

Before the 20th century, the Universe was a quiet place. Not much seem to happen.

Most physicists assumed the Universe to be infinite in space and time.

However, there was a strange observational fact:

It is dark at night.

This could not be explained with an eternal and infinite universe

Olber's "Paradox"

Heinrich Wilhelm Olbers (1823)

If the universe is endless and uniformly populated with luminous stars, then every line of sight must eventually terminate at the surface of a star.

Formally:

Each shell contributes $\sim r^2$

The light decreases with $\sim 1/r^2$

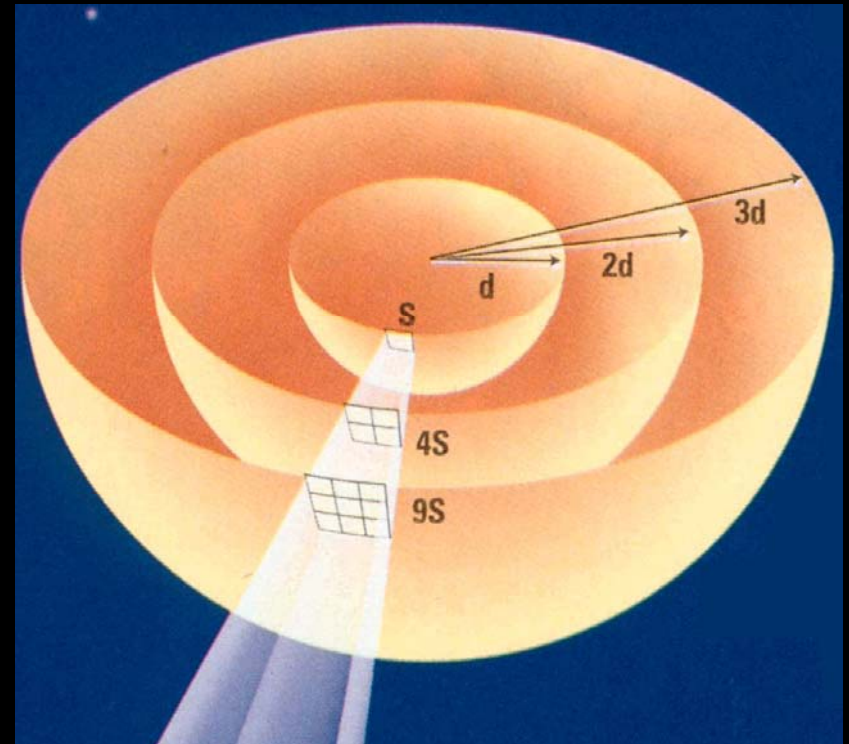
Light contribution from each shell = constant

Consequence:

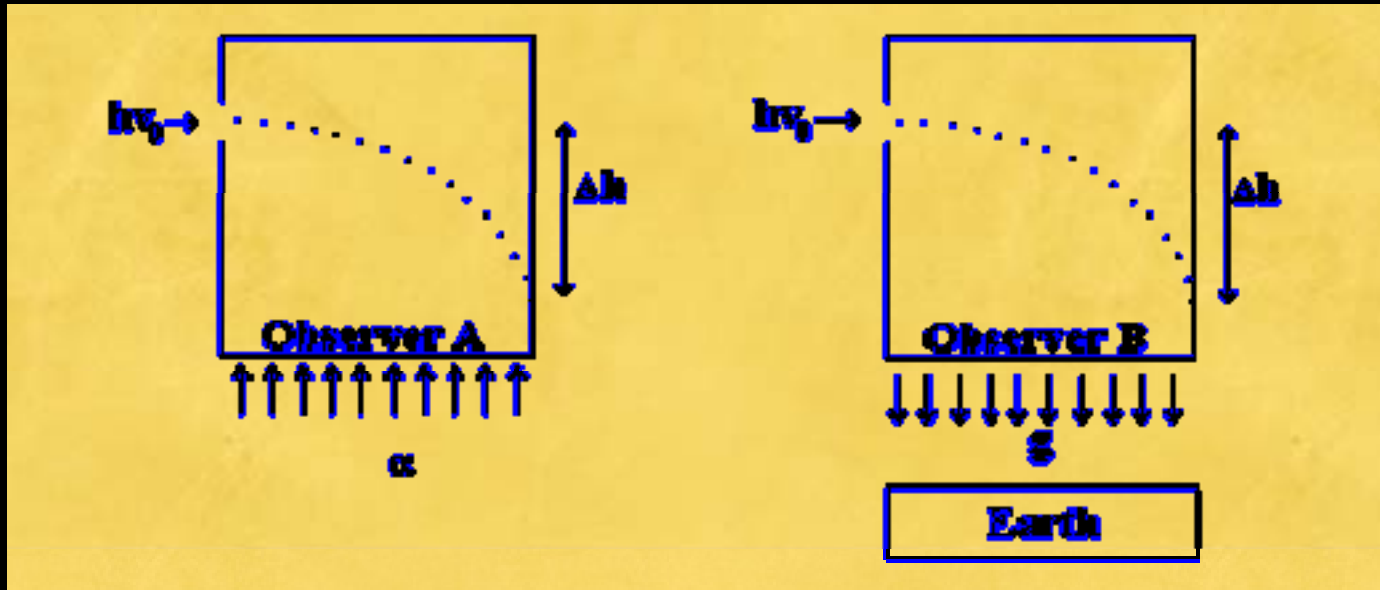
The Universe did not exist forever, or ...

The Universe has a finite size, or ...

Both



Equivalence Principle



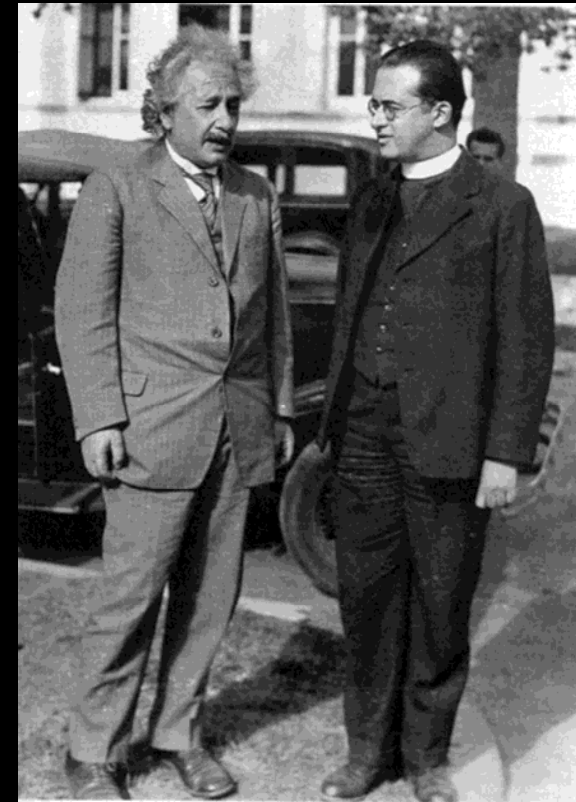
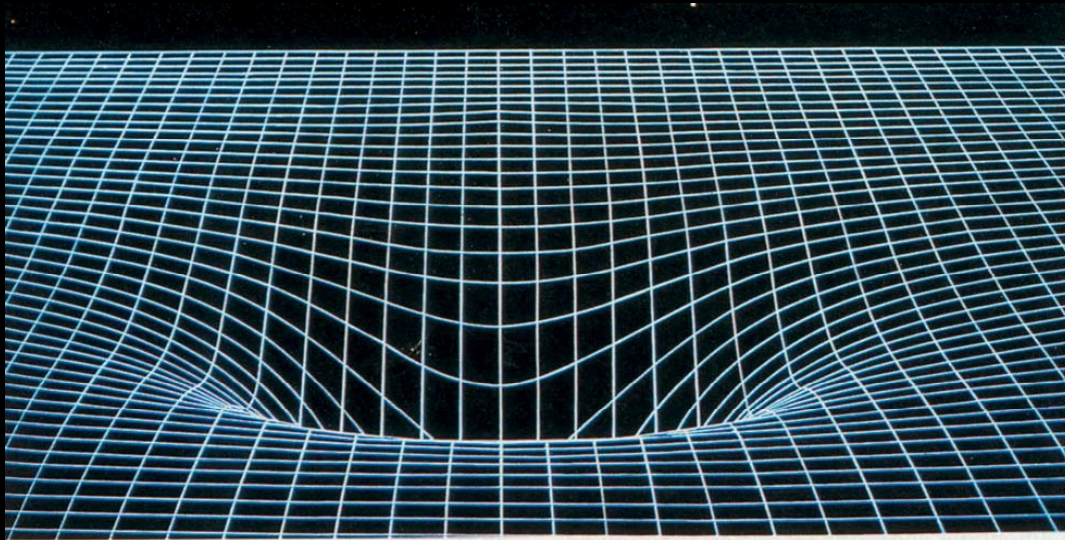
Acceleration (inertial mass) is indistinguishable from gravitation (gravitational mass)

"The happiest thought of my life" (Albert Einstein)

Light rays define the shortest path in space.
Accelerated elevator: light follows a parabolic path
Gravitational field: light path must be bent !
Space and time must be curved

Albert Einstein (1912-15) : General Relativity

Matter tells Space how to curve
Space tells Matter how to move



George Lemaitre (1927)

The whole Universe expands
A 'hot primordial atom' ?

Universe

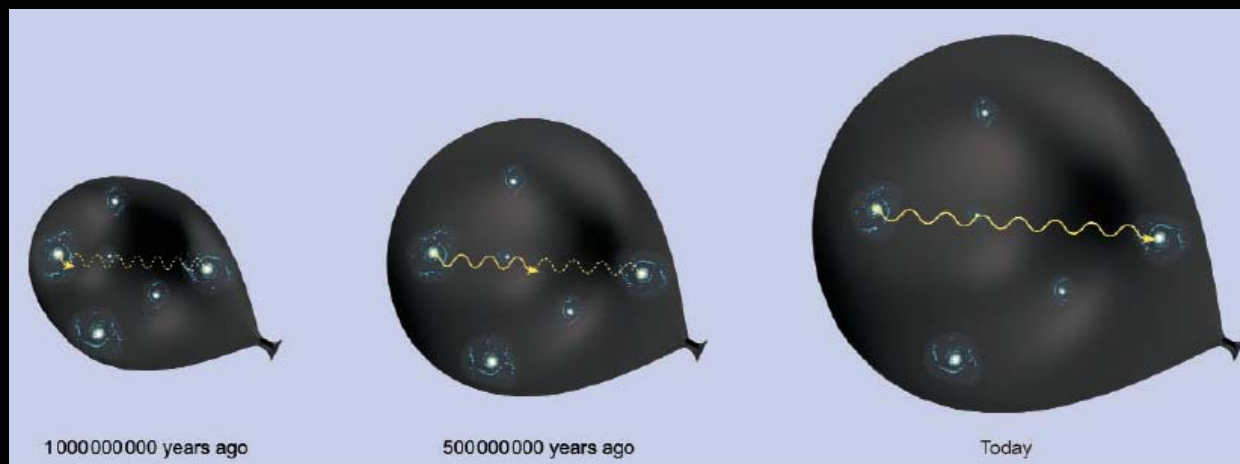
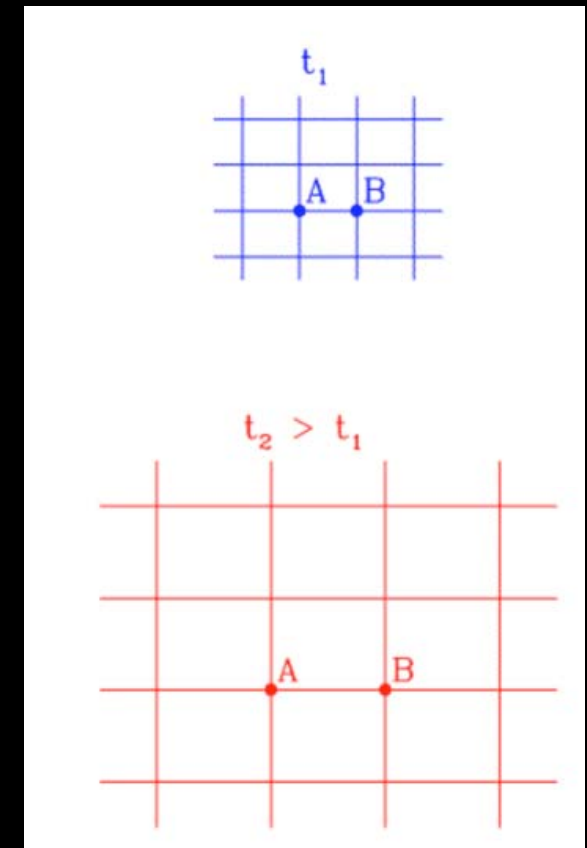
1915

Friedmann described the expansion of the Universe using a scale factor $a(t)$

$$r_{AB}(t) = a(t)x_{AB}$$

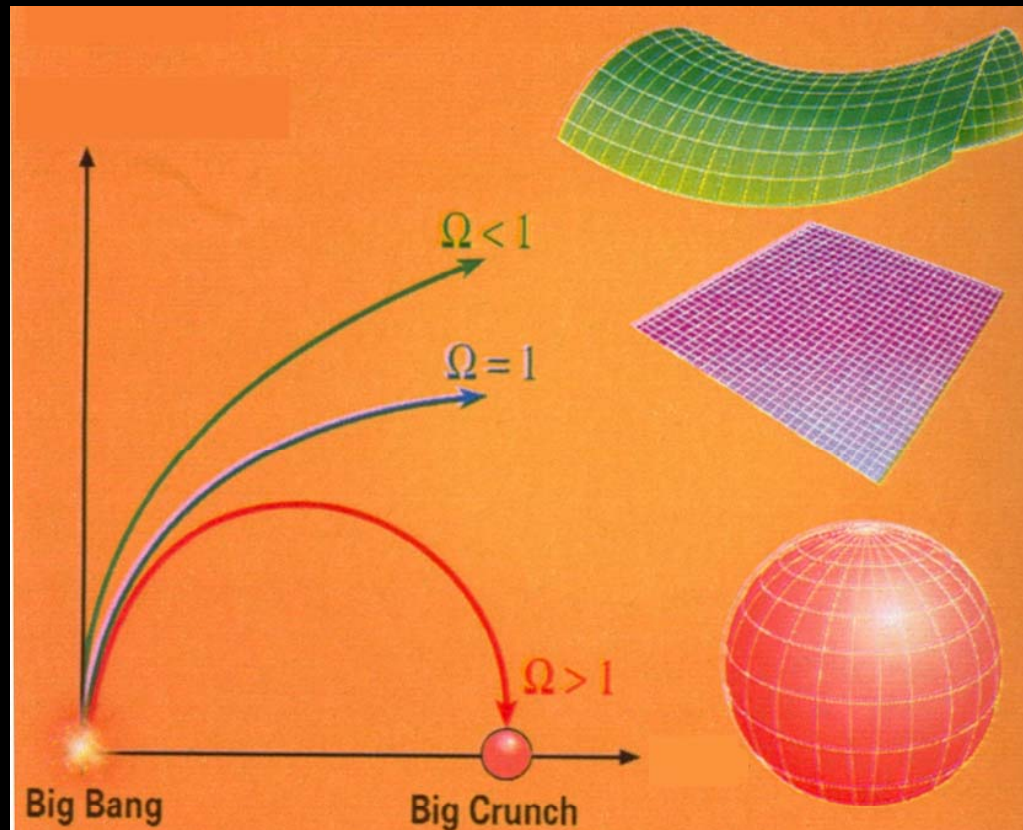
His equation relates the average energy density " ρ " and the curvature factor K with the expansion rate

$$\left(\frac{1}{a} \frac{da}{dt}\right)^2 = \frac{8\pi G}{3} \bar{\rho} - \frac{K}{a^2}$$



Universe

The crucial question was the mass of the Universe. In principle, it could be anything. However - there is a 'critical energy density'. If the average energy density is larger, the Universe will stop expanding and fall back into a big crunch one day ('deceleration' parameter)



Universe


Einstein did not like the idea of a 'dynamic' Universe.

He believed in an eternal and static Universe.

But his own equations predicted something else.

Therefore he decided to tinker with them, by adding a term named

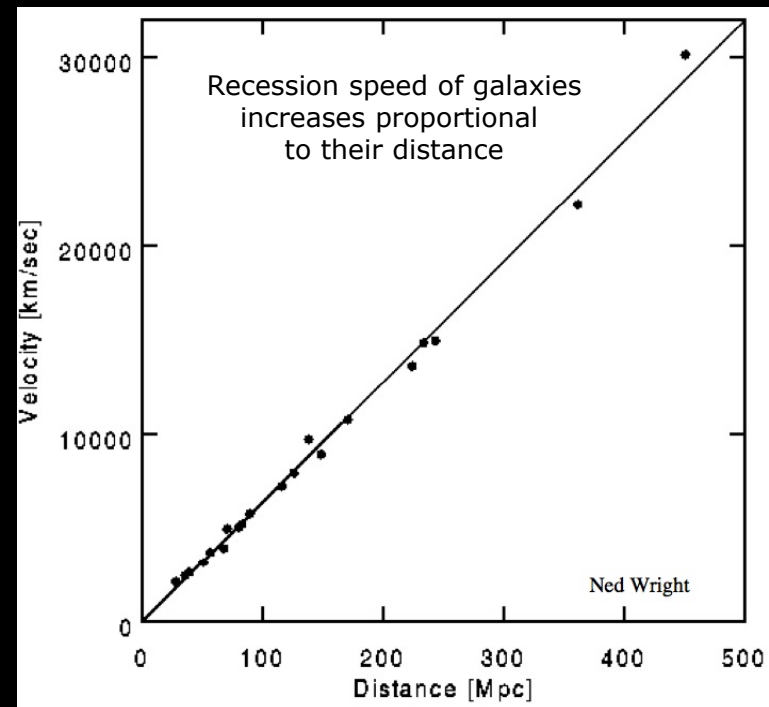
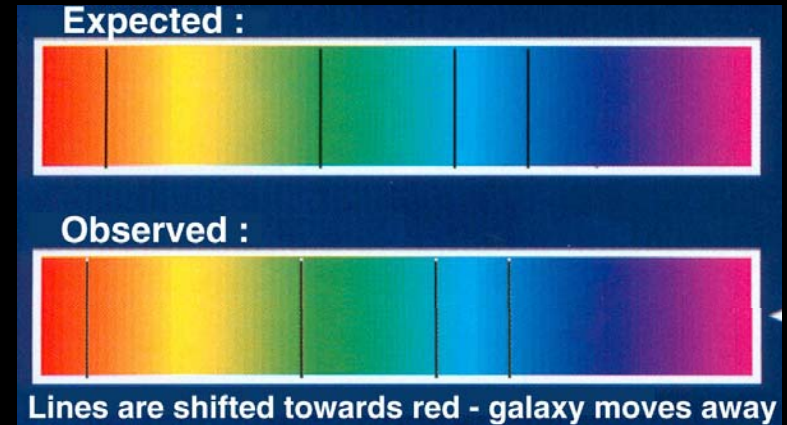
'cosmological constant'


$$\left(\frac{\dot{R}}{R}\right)^2 - \frac{8}{3}\pi G\rho - \frac{1}{3}\Lambda c^2 = -\frac{kc^2}{R^2}$$

Universe



Edwin Hubble (1929)
Mt. Palomar telescope



Einstein concedes: cosmological constant 'my biggest blunder'

Universe

Observation of many stars and galaxies revealed an **amazing fact**:

The Universe is the same in every direction, at any distance ...

Hydrogen ~ 75 %

Helium-4 ~ 25 %

He-3 ~ 0.003 %

Deuterium ~ 0.003 %

Li-7 ~ 0.00000002 %

There must be a reason ...

1948: The 'Big Bang' model* of the beginning of the Universe



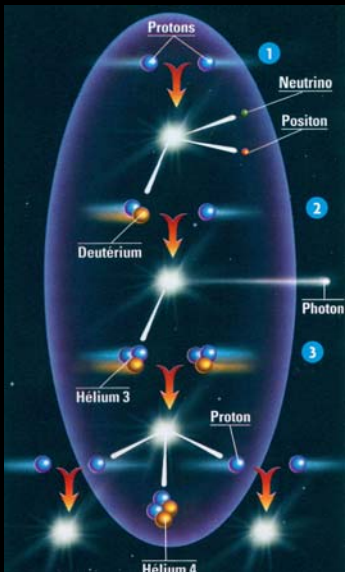
George Gamov

The Universe started from an extremely hot initial state

Then it expanded rapidly, while cooling down

In very early times, the Universe was mostly radiation

Radiation produced particles (protons, neutrons, electrons)



- In the first few minutes, there was just enough time to create the lightest elements
- There should be an 'echo' in form of a uniform black-body radiation ($T \sim 5 \text{ K}$)

* The name 'Big Bang' was used by Fred Hoyle to ridicule Gamov's idea. Later Fred Hoyle was ridiculed.

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Weak

Strong

Detector

Accelerator

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p^+

n

Dirac
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Galaxies; expanding
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Dark Matter

Nuclear fusion

Synchrotron

Big Bang
Nucleosynthesi
s

Bubble

Cosmic Microwave
Background

e^+e^- collider

Wire chamber

Beam cooling

Online computers

Inflation

p^+p^- collider

Modern
detectors

CMB Inhomogeneities
(COBE, WMAP)

WWW

Dark Energy (?)

GRID

5

6

Particle
zoo

QED

P, C, CP
violation

W bosons

Higgs

EW unification

QCD

Colour

GLU

SUSY

Superstrings

W

Z

g

3 generations

STANDARD MODEL

ν mass

t

ν_μ

ν_e

τ^-

τ^+

μ^-

μ^+

e^-

e^+

p^+

n

π

π

π

π

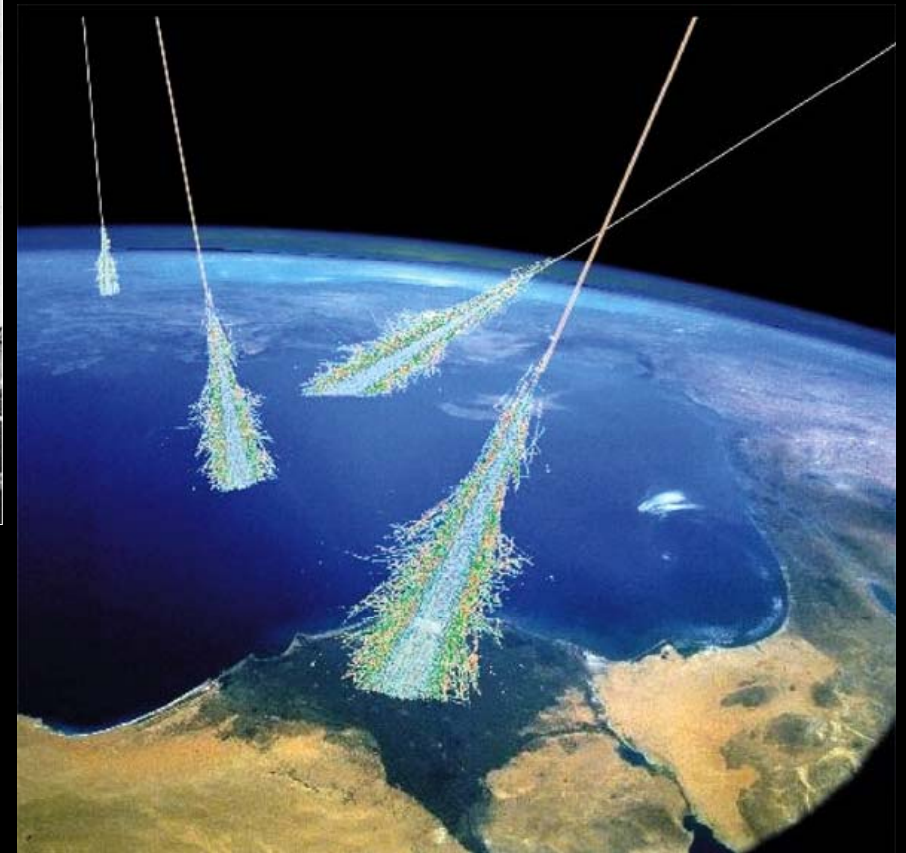
π

In 1913, first hints of a violent universe appeared

Discovery of cosmic rays

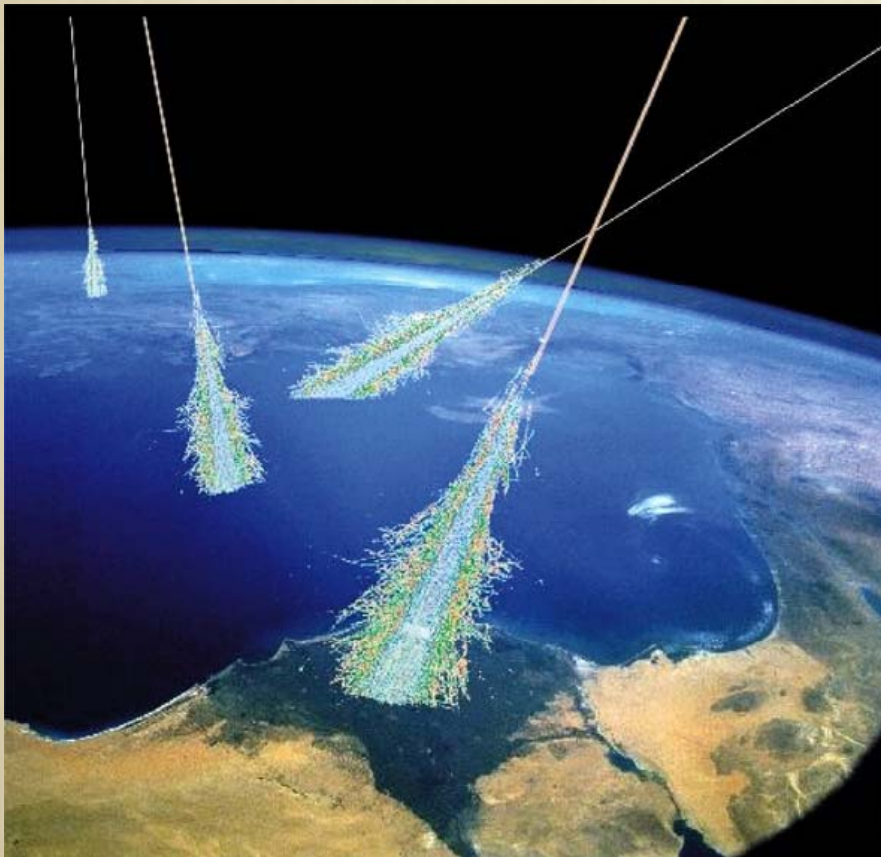


Victor Hess



After Yukawa's prediction of a 'pion' (1934), everybody was searching for this particle (100-200 MeV).

There was no accelerator with sufficient energy available (yet). So physicists went on mountain tops to search for tracks in their photographic emulsions.



**A new particle was discovered
in the right mass range**

But: very long range in matter !! ?

That means: no (strong) interaction with nuclei, and therefore not Yukawa's pion !

Muon - 'heavy electron' ($206 \times m_e$)

I. Rabi: "WHO ORDERED THAT ?"

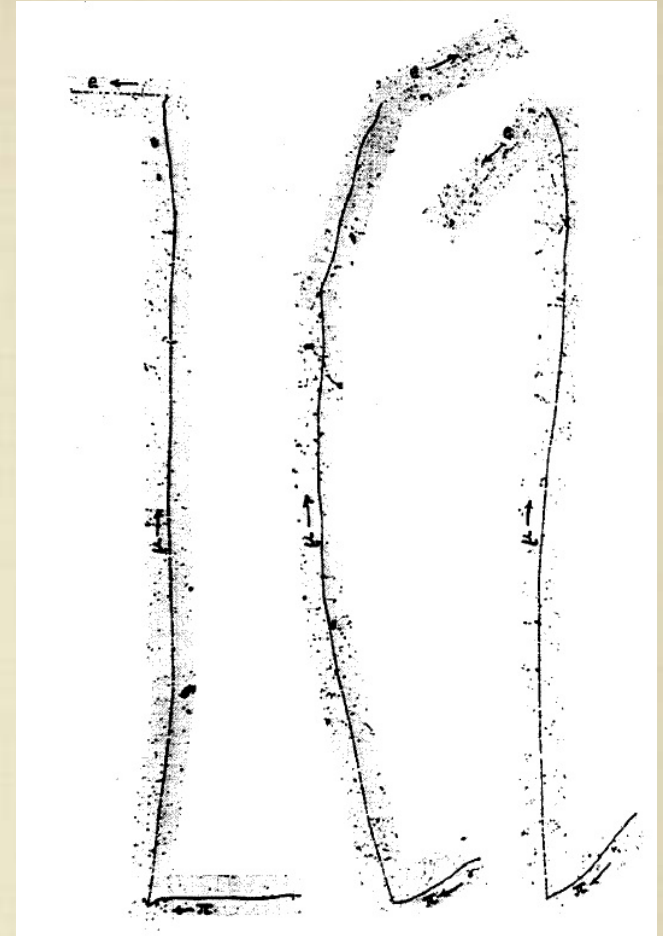
Discovery of the (charged) pion



Scanned at the American
Institute of Physics

Cecil Powell

Ouff!



Photographic emulsion technique

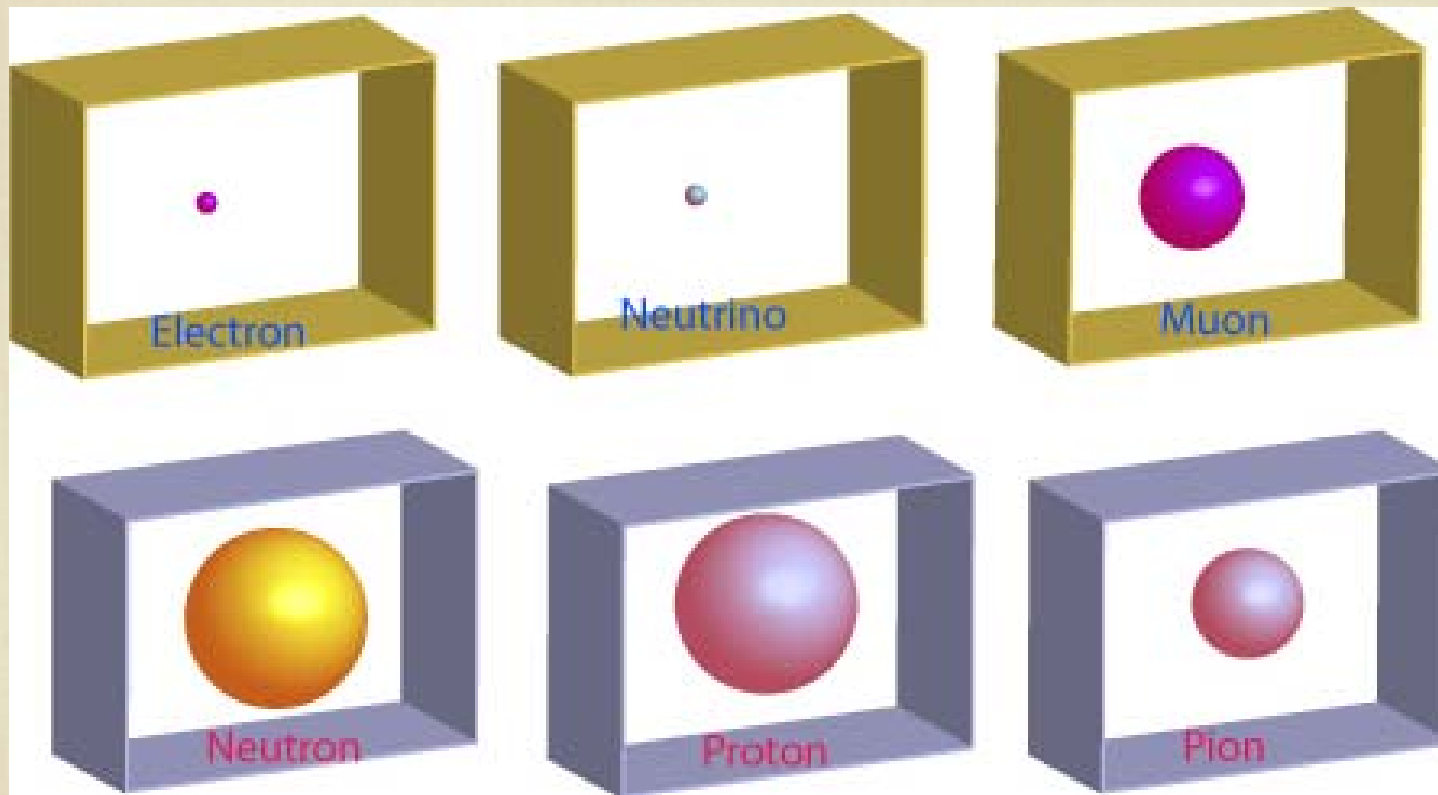
Cosmic rays at **high altitude** (Pic du Midi, Pyrenees)

Pion tracks identified under microscope

One year later: Pions produced at Berkeley cyclotron (Alpha+Carbon)

PARTICLE SPECTRUM

1948



PARTICLE SPECTRUM

1931 - 1955

Accelerators

"Man-made cosmic rays"

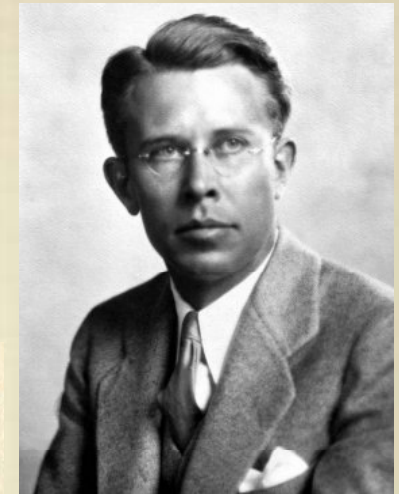
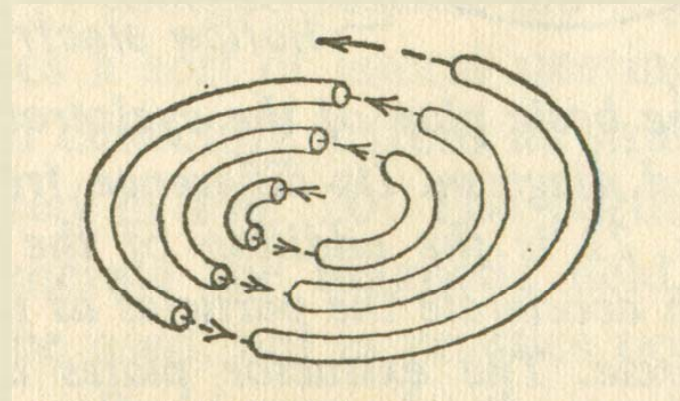


Rolf Wideroe, 1928



Linear accelerator

Accelerate particles between electrode gaps
Tune RF frequency to match particle motion



Ernest Lawrence, 1931

Cyclotron

Use magnetic field to bend particles into circular orbit
Particles pass through same accelerating gap many times and reach higher energies

1931: 80 keV

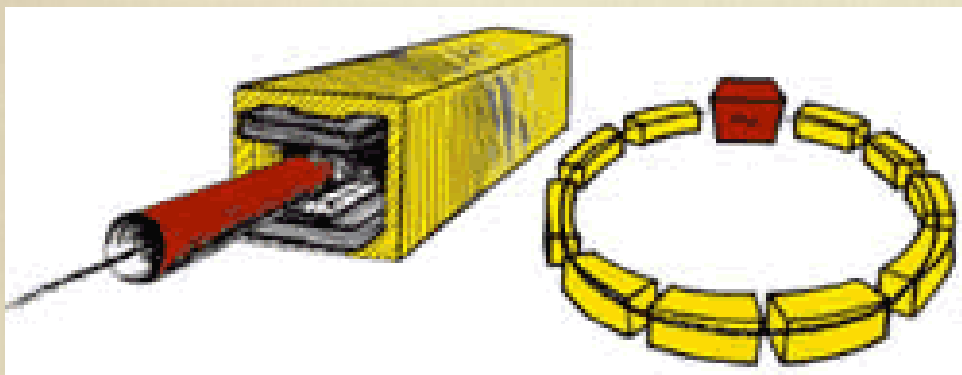
1932: 1000 keV

1939: 19 MeV*

1946: 195 MeV ("synchrocyclotron")

* first limitations by relativistic mass increase

Accelerators (2)



Synchrotron

Similar to cyclotron, but change magnetic field to keep particles on the same orbit
(also overcomes relativistic mass increase)

1947: US constructs two 'synchrotrons'

Brookhaven (1952) - 3 GeV

Berkeley (1954) - 6.2 GeV ('antiproton')

1954: Europe competes with US

CERN (1959) - 24 GeV

Brookhaven (1960) - 30 GeV

Detectors

Geiger counters
Cloud chambers
Emulsions
Bubble chambers

Cerenkov counters
Photomultipliers
Spark chambers

After 1967:

Wire chambers
Drift chambers
Calorimeters

Particle e zoo

PARTICLE SPECTRUM

1950- 1968

With new accelerators and detectors,
the "particle zoo" grew to more than ~ 200 'elementary particles'

$\pi^+ \pi^- \pi^0$

Pions

$K^+ K^- K^0$

Kaons

η'

Eta-Prime

η

Eta

ϕ

Phi

$\rho^+ \rho^- \rho^0$

Rho

Mesons

$\Delta^{++}, \Delta^+, \Delta^0, \Delta^-$

Delta

Λ^0

Lambda (strange!)

$\Sigma^+, \Sigma^0, \Sigma^-$

Sigma (strange!)

Ξ^0, Ξ^-

Sigma(very strange!)

BARYONS

What was the underlying structure ?

SU(3) - Classification scheme based on 'quarks'



Fig. 6.35 Murray Gell-Mann (b.1929).

Gell-Mann, 1963

(G. Zweig, 1963, CERN)

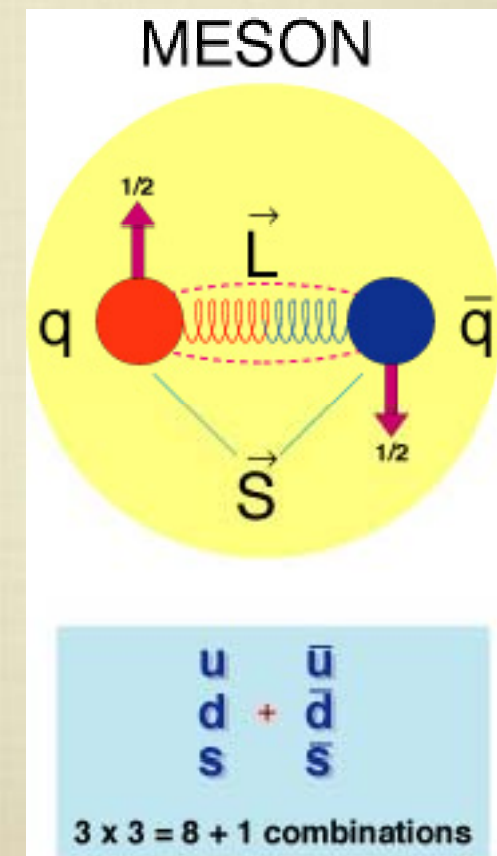
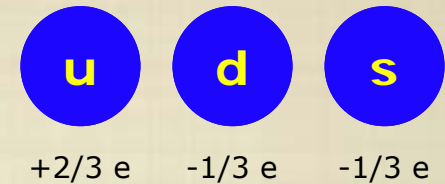
1) 3 types of "quarks" : up, down, strange

2) Carry electric charges: $+2/3$, $-1/3$, $-1/3$

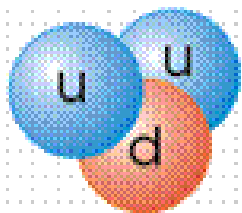
3) Appear in combinations:

Meson = quark+antiquark

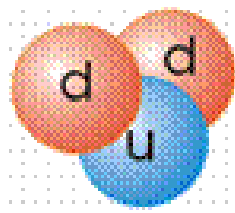
Baryon = quark(1) + quark(2) + quark(3)



The Proton

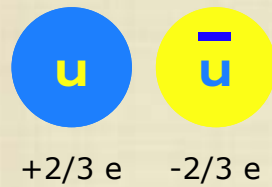


The Neutron

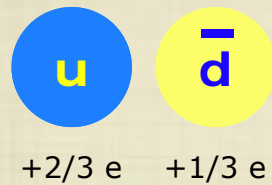


PARTICLE SPECTRUM

Some mesons (quark+antiquark):



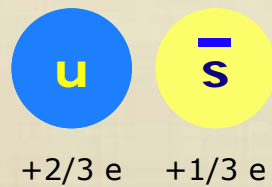
π^0



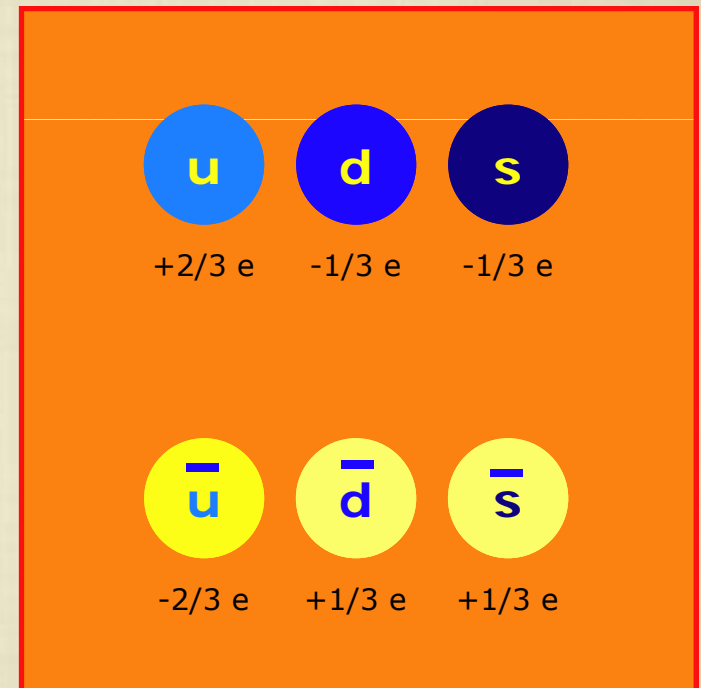
π^+



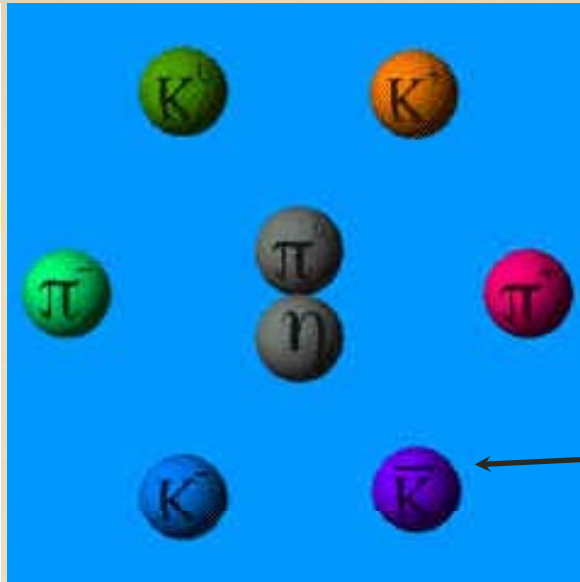
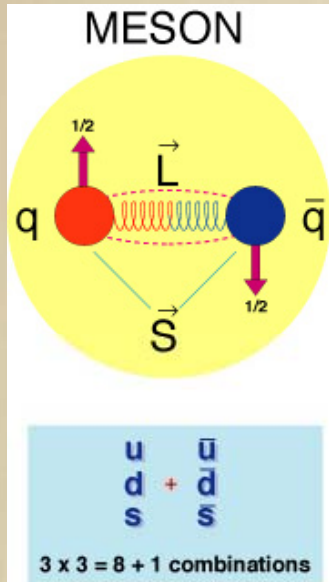
π^-



K^+



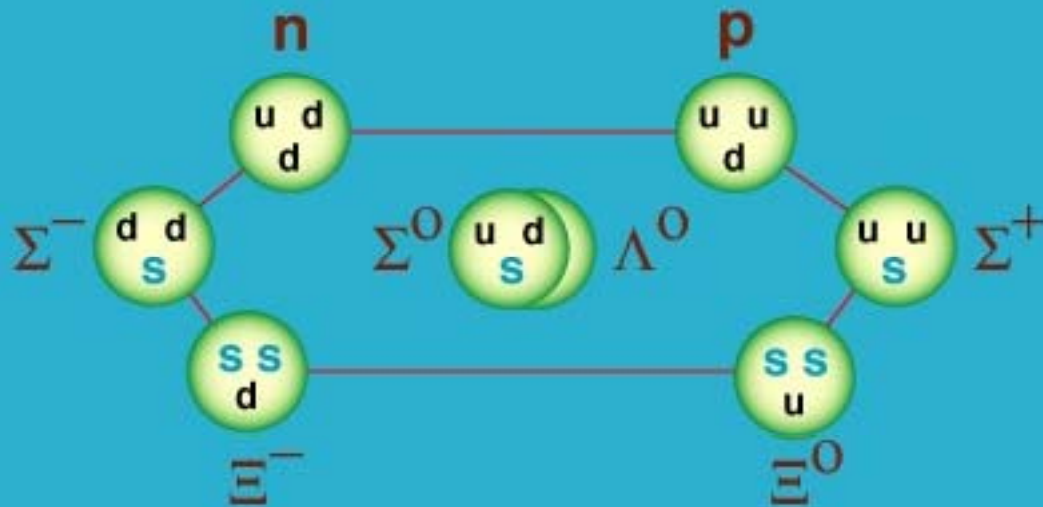
PARTICLE SPECTRUM



← Pion, Eta-meson

← Kaons have a strange quark

SPIN 1/2 BARYON OCTET

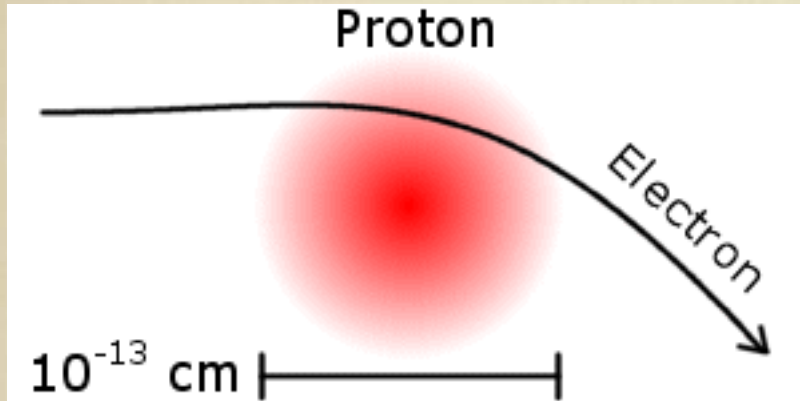


Ground state baryons:
Proton, Neutron;
Lambda, Sigma, Xi

PARTICLE SPECTRUM

Discovery of quarks

Electron-Proton scattering

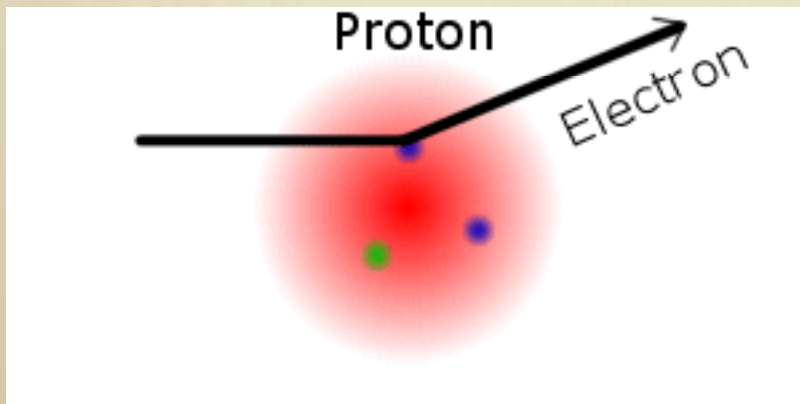


1956 Hofstadter: measured finite proton radius



Stanford Linear Accelerator Centre

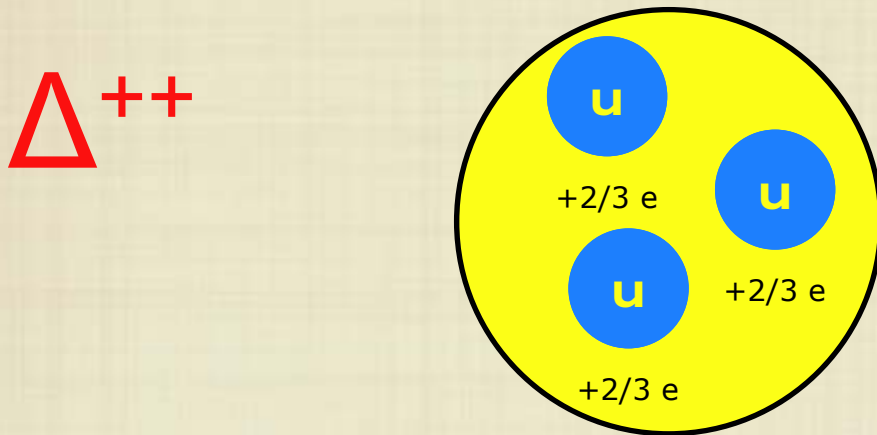
1967 Friedmann, Kendall, Taylor (SLAC):
'hard scattering' of electron on three 'point-like particles'



Measured cross-sections perfectly compatible with presence of 2 up- and 1 down-quark in proton

The concept of “Colour” charge

PROBLEM: three fermions are not allowed to be in identical states (Pauli exclusion principle)



Since the three up-quarks must have parallel spin -
there are in a symmetric state

The three quarks must be different in one quantum number: “colour”

(Bardeen, Fritzsche, Gell-Mann)

PARTICLE SPECTRUM

Quantum Chromo Dynamics

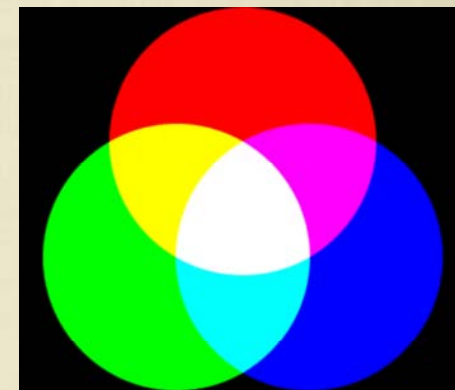
this has nothing to do with our visible colours, just an analogy

Theory constructed in analogy to QED

QCD: 3 different charges ("colour charge") [red, green, blue]*

'Strong force' between quarks is transmitted by (8) gluons

GLUONS CARRY COLOUR CHARGE - SELF-INTERACTION !



Dogma of QCD: Only colour-neutral bound states are allowed

MESONS = Quark-Antiquark

BARYONS = 3-Quark states

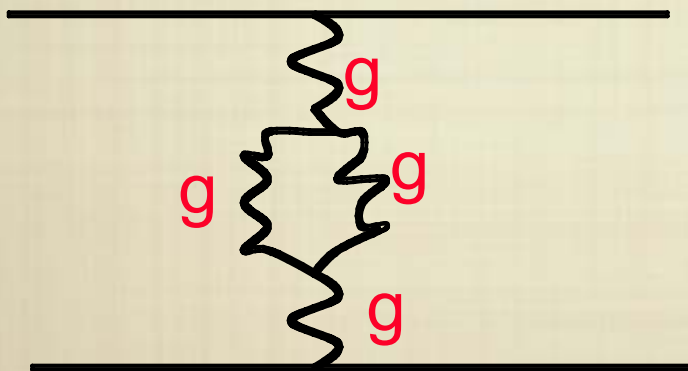
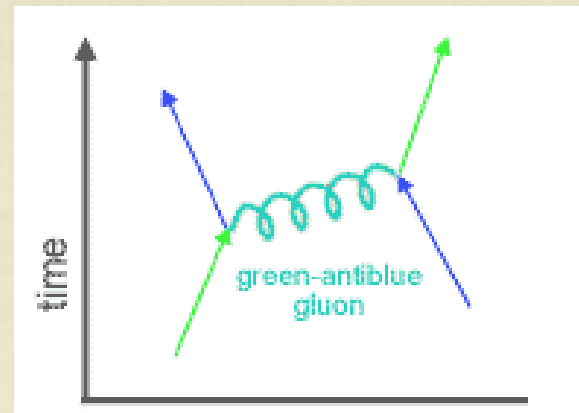
Gluons



Gluons are massless carriers of the strong force

There are $3 \times 3 - 1 = 8$ different gluons

Gluons carry colour charge \rightarrow self-interaction



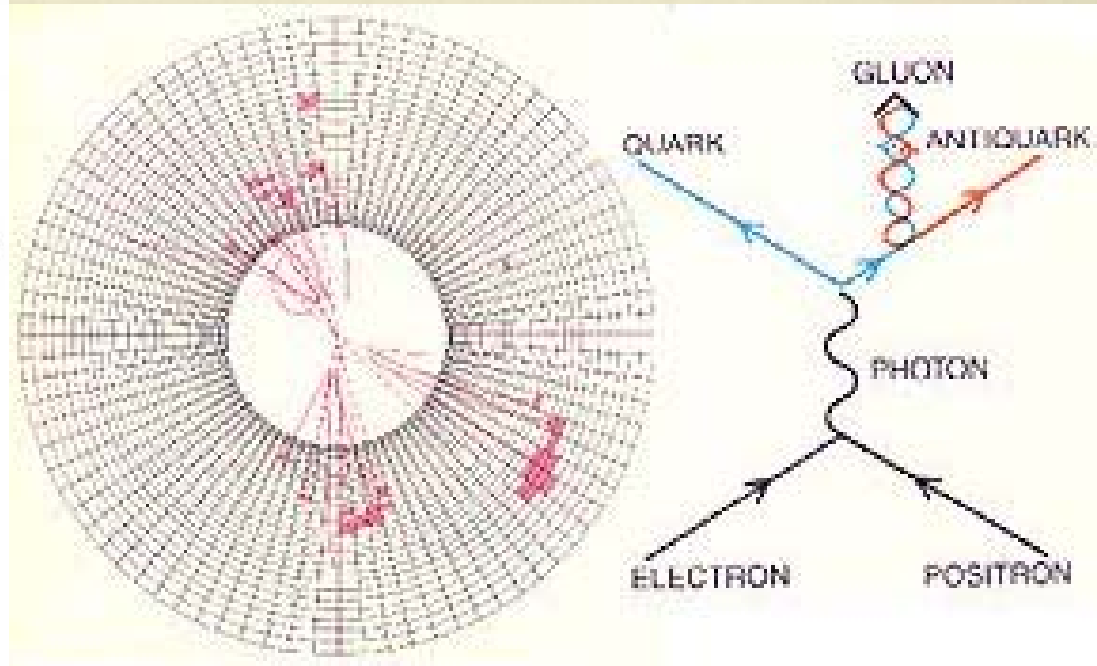
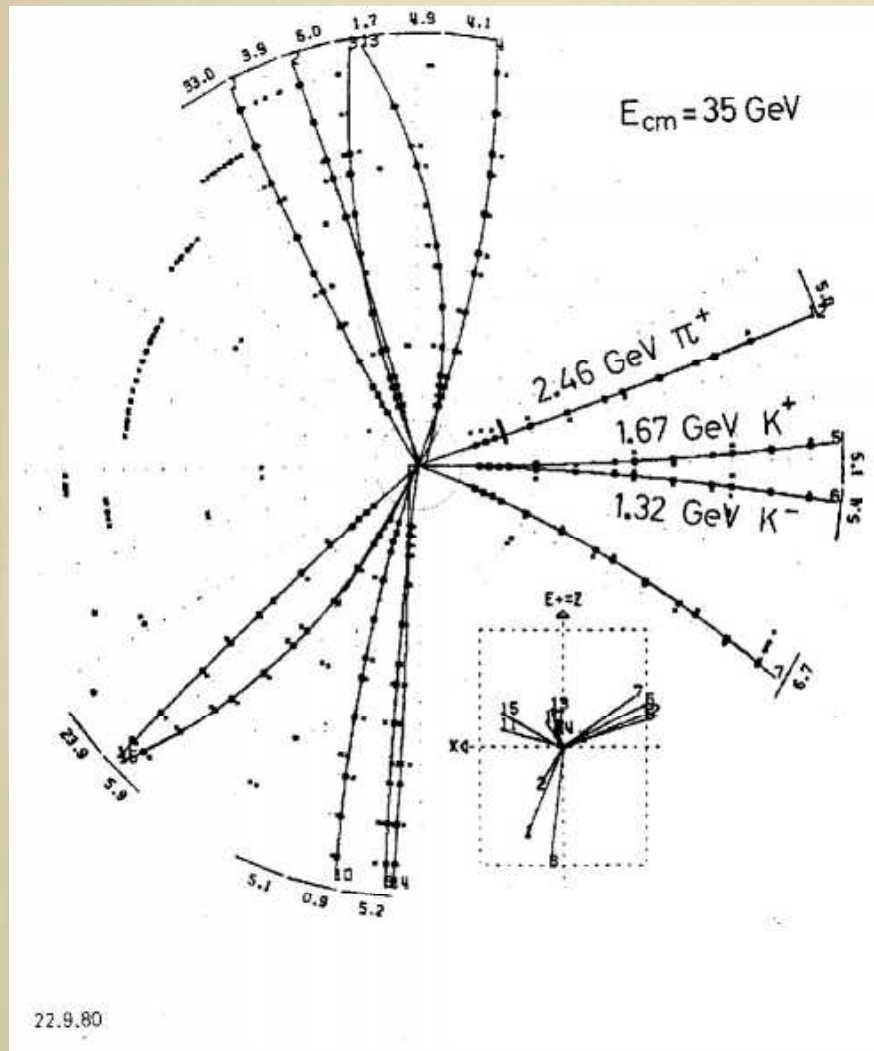
Self-interaction of gluons

Potential rises linearly with distance (for large r)

$$V_{QCD} = -\frac{4}{3} \frac{\alpha_s}{r} + kr$$

Small distances: asymptotic freedom

Discovery of Gluons

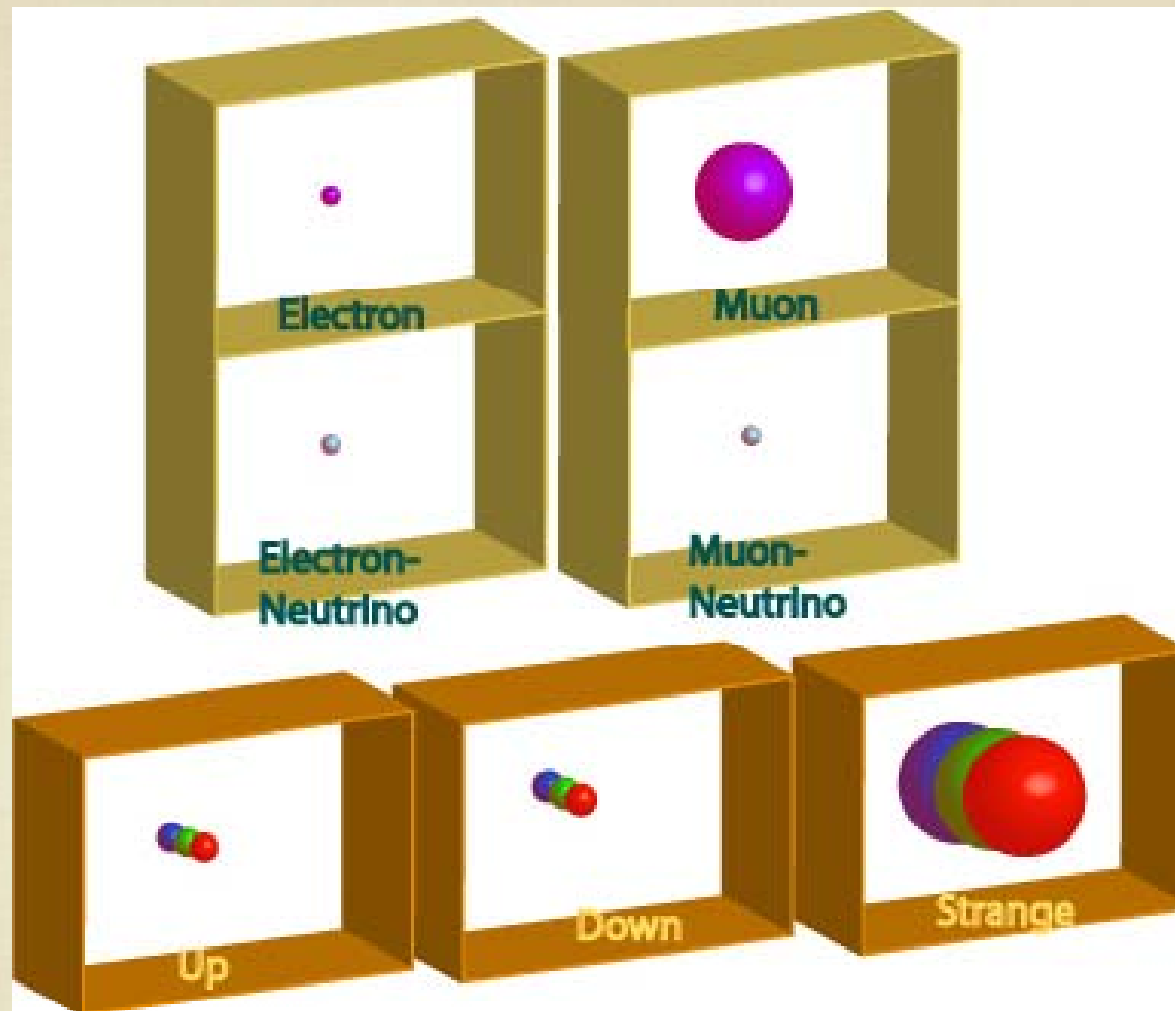


PETRA Storage Ring, 1979, DESY (Hamburg)

PARTICLE SPECTRUM

1973

LEPTONS



QUARKS

Connection?

KEY: 'electroweak' interaction and the 'flavour' of elementary particles

Fields

Electroweak Interaction

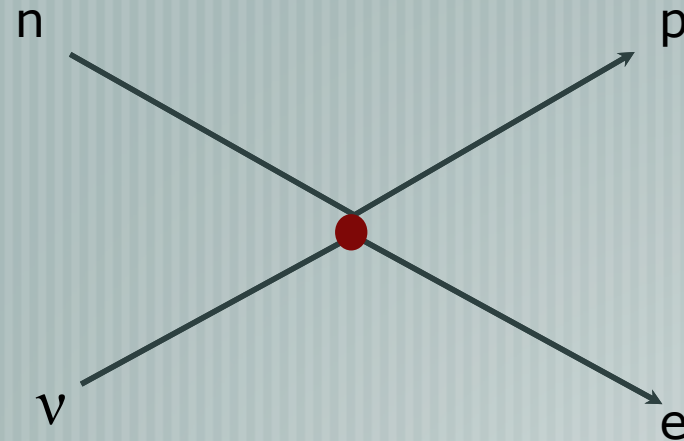
1958 Glashow

There was a big (theoretical) problem:

Neutrino-Proton cross-section $\sim (G_F E_V)$

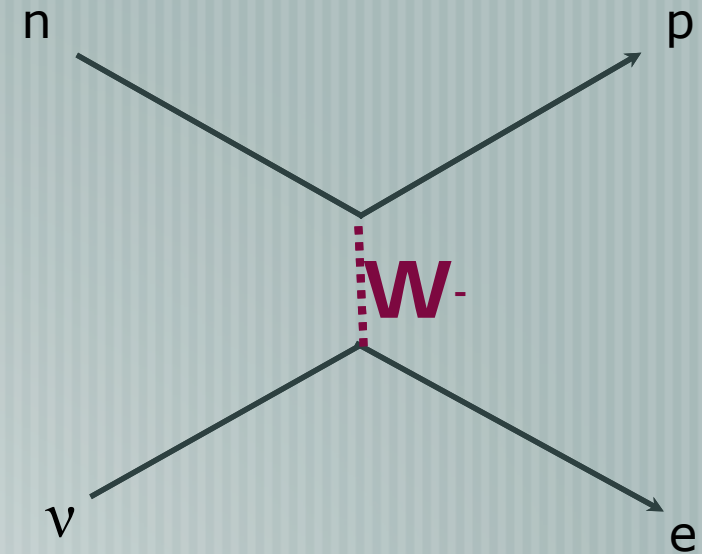
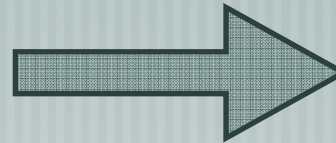
violates conservation of probability* for $E > 300 \text{ GeV}$

(the probability of the interaction becomes $> 100\%$)



Fermi model

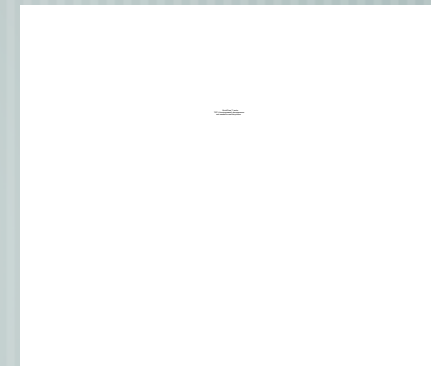
New Idea



Glashow model

**Weak interaction transmitted by massive vector bosons
(in analogy to photon exchange!)**

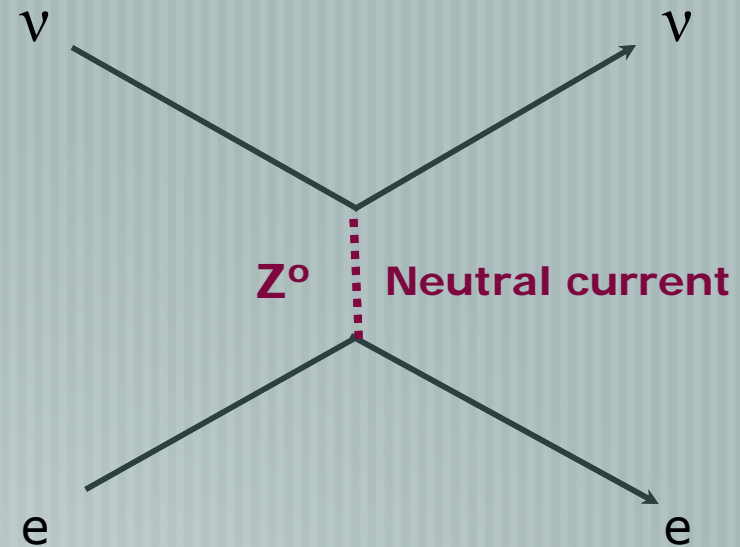
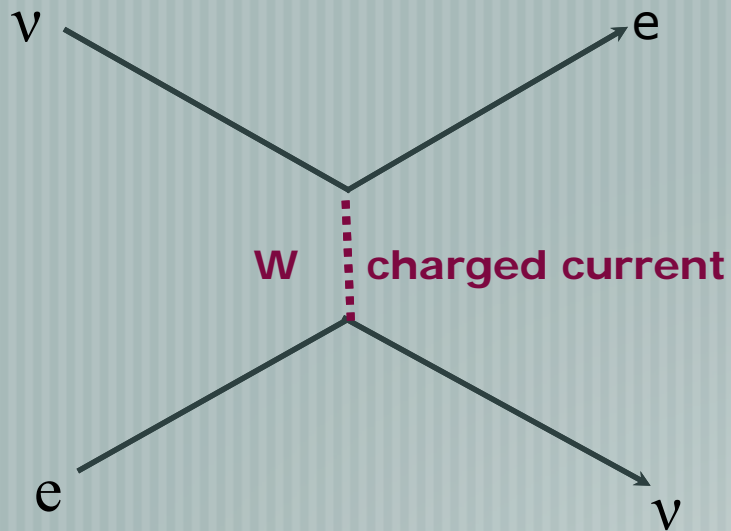
**Large mass (80 GeV) explains
short range ($2 \cdot 10^{-18} \text{ m}$) and small cross-sections**



Fields

Electroweak Interaction

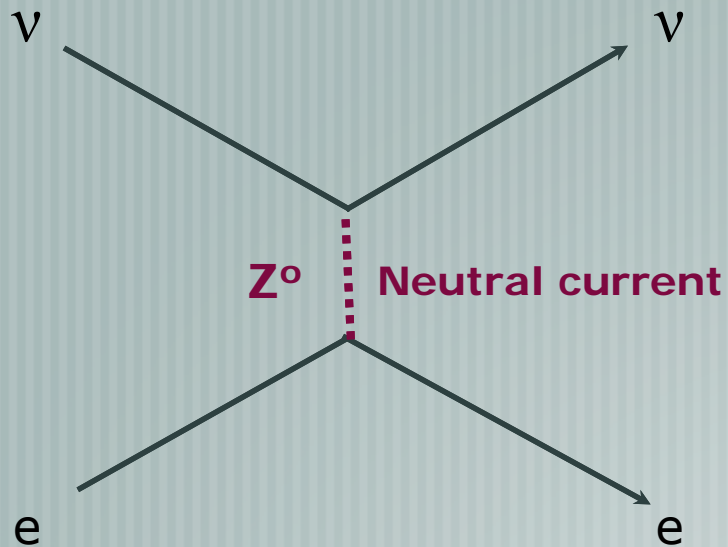
1968



Glashow, Salam, Weinberg (1968) - Electroweak Force

- The electromagnetic and weak interaction are different aspects of the same 'electroweak' force
- All quarks and leptons have a 'weak' charge
- There should be a 'heavy photon' (Z^0) and two charged vector boson (W^\pm) of mass ~ 50 - 100 GeV
- **The W, Z bosons acquire their mass by interacting with the "Higgs field" (1964)**
- There are only 'left-handed' interactions

Discovery of neutral currents at CERN (1973)



- Neutrino beam directed on a bubble chamber
- An electron track emerges out of 'nowhere'

Nuclear Physics B73 (1974) 1–22 North-Holland Publishing Company

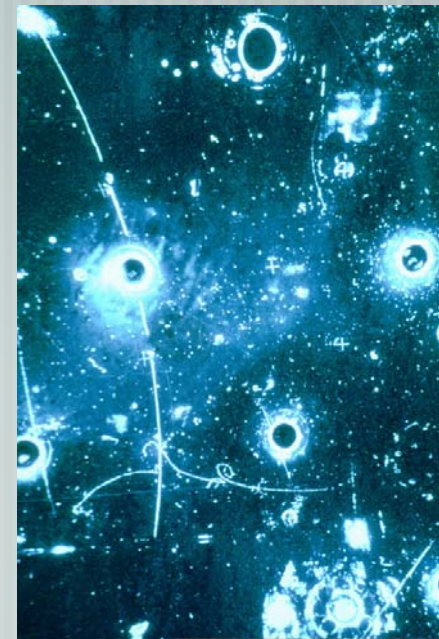
OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

F.J. HASERT, S. KABE, W. KRENZ, J. VON KROGH, D. LANSKE,
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D. HAIDT, S. NATALI†, P. MUSSET, B. OSCULATI, R. PALMER††,
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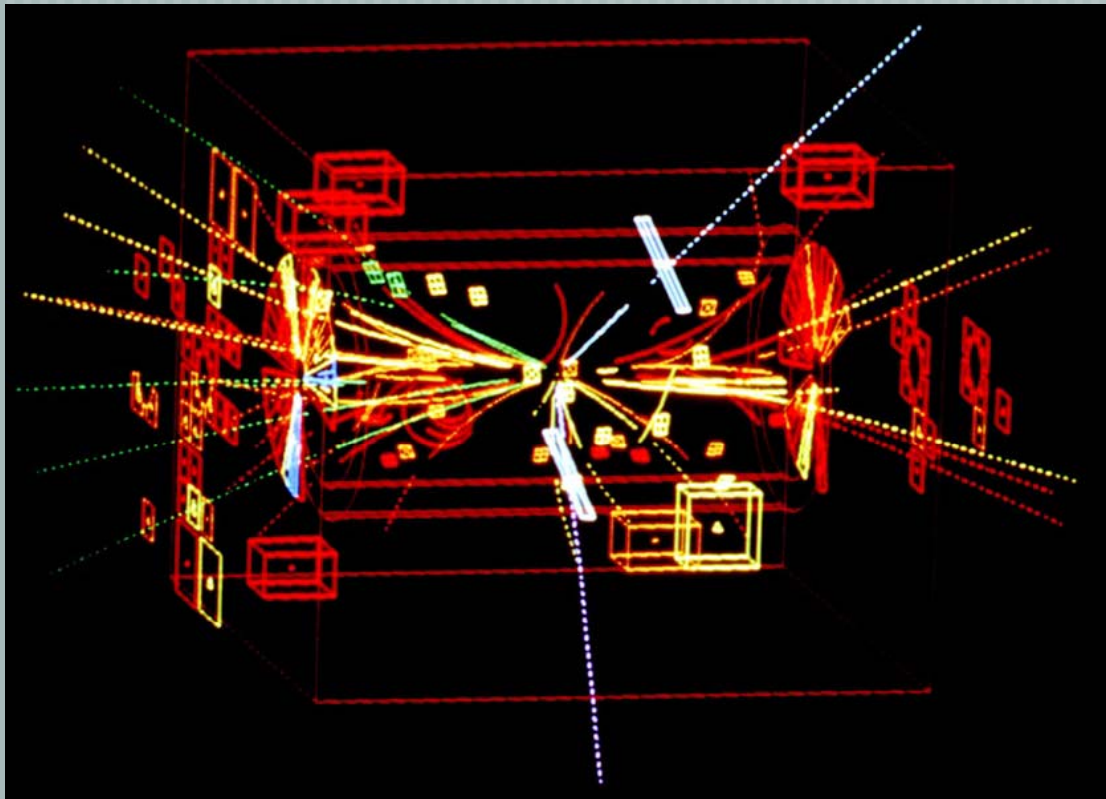
Fields

Electroweak Interaction

1983

Discovery of the W, Z bosons at CERN (1983)

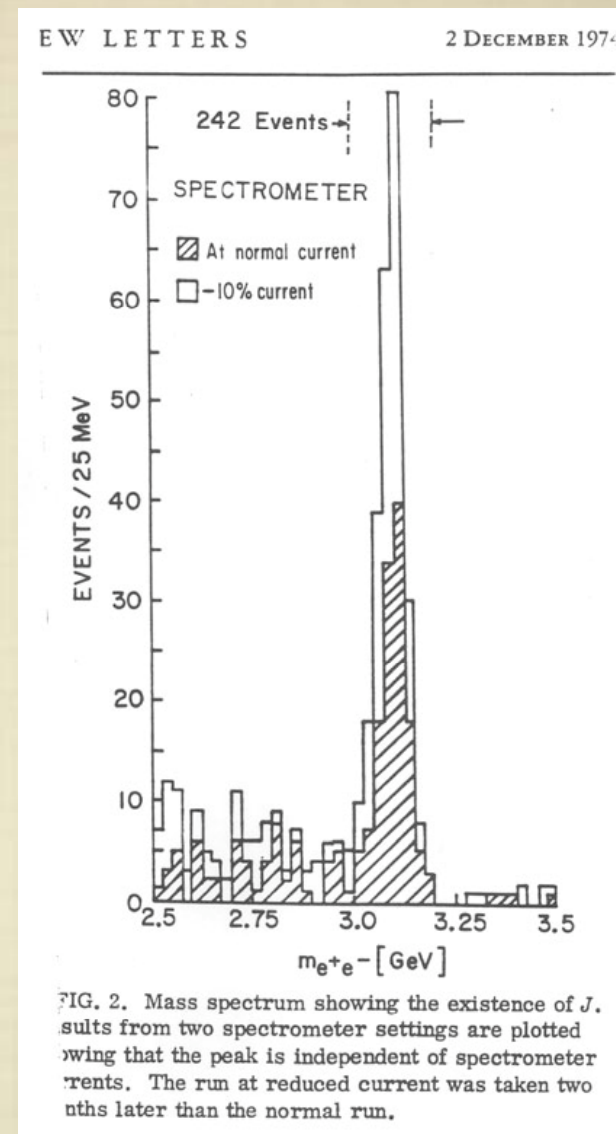
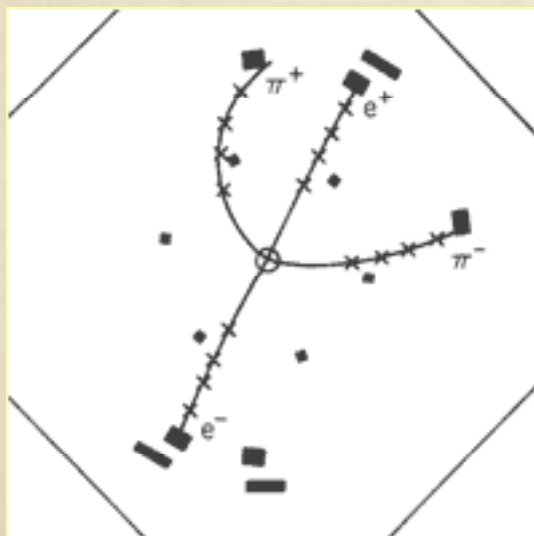
(Carlo Rubbia - leader of UA1 collaboration, and proponent of proton-antiproton collider in SpS)
(Simon van der Meer - inventor of stochastic beam cooling)



And the charm quark was to be discovered soon afterwards :

The NOVEMBER REVOLUTION (11 November 1974)

Two groups discovered ~ simultaneously a new particle, which they called '**Psi**' at SLAC (Burt Richter) and '**J**' at Brookhaven (Sam Ting).



The J/ψ resonance was 'long-lived' ($\sim 10^{-20}$ sec). It could only decay by weak interactions, preferably into an s-quark. This explains the narrow peak.

Milestone paper (Glashow, Iliopoulos, Maiani)

PHYSICAL REVIEW D

VOLUME 2, NUMBER 7

1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

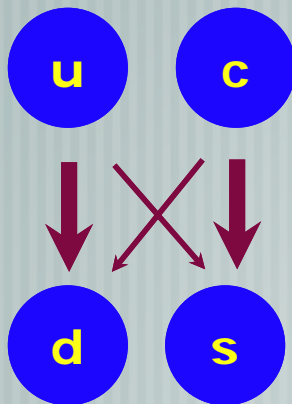
S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

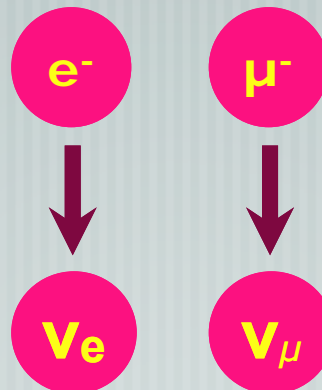
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.

Quarks



Leptons



*This was now called
the 'Standard Model'
(with two families)*