STRUCTURE OF MATTER

Discoveries and Mysteries

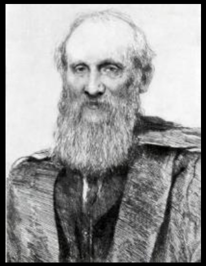
Rolf Landua
CERN

PREFACE

This is a lecture about 100 years of particle physics.
It covers about 100 years of ideas, theories and experiments.

More than 50 Nobel prize winners on particle physics
This is a broad overview about the main discoveries.

In the early 1900s, most physicists believed that physics was complete, described by classical mechanics, thermodynamics, and the Maxwell theory.



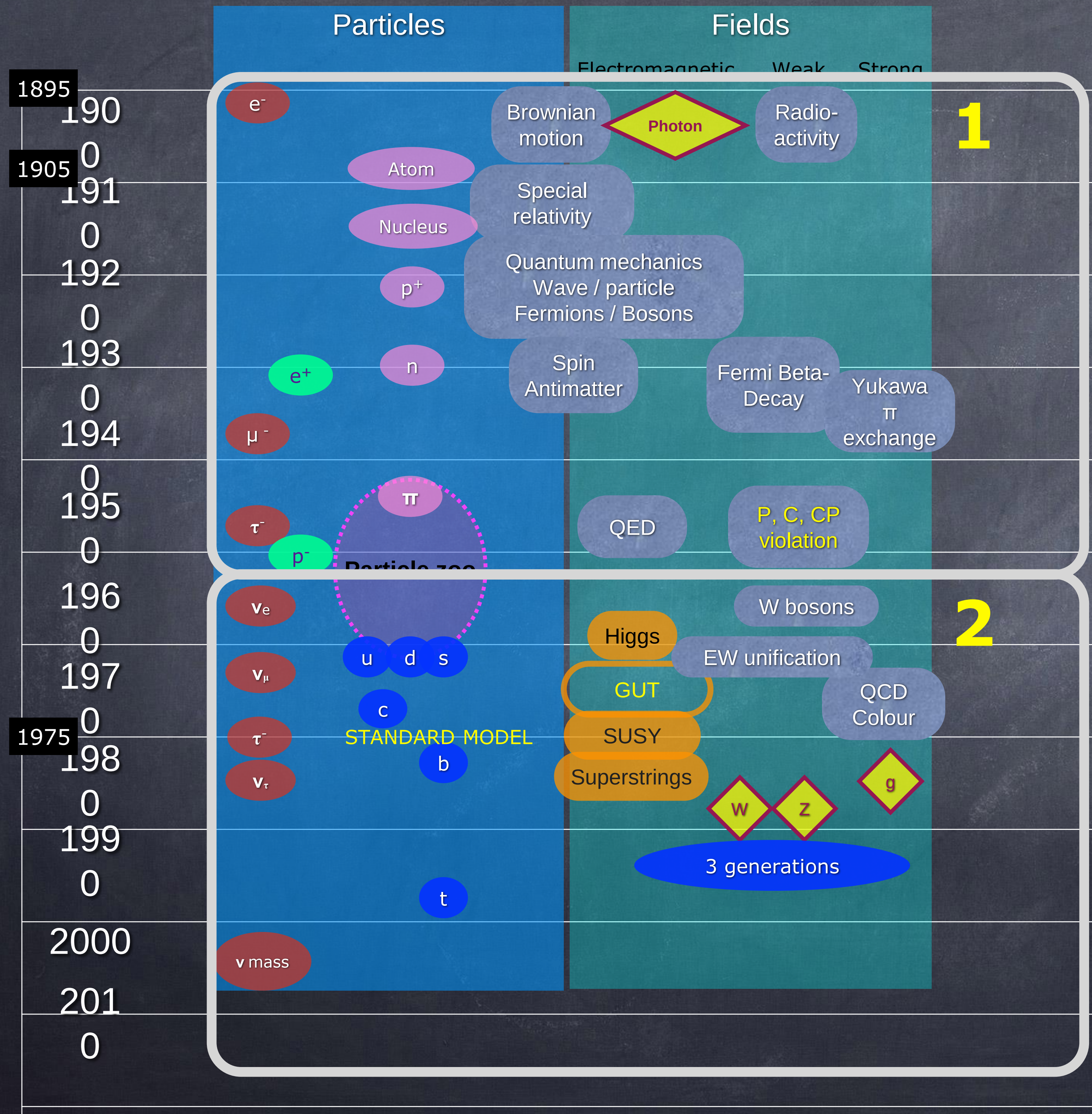
Lord Kelvin

“There is nothing new to be discovered in physics now. All that remains is more and more precise measurement. “ (Lord Kelvin, 1900)

DARK CLOUDS:

1) Blackbody radiation - Quantum Physics

2) Michelson-Morley experiment - Special Relativity



Particles
Fields
Electromagnetic
Weak
Strong
1895
1905
1975
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
e⁻
Atom
Nucleus
p⁺
n
e⁺
μ⁻
π
τ⁻
p⁻
Particle zoo
νe
νμ
τ⁻
ντ
u
d
s
c
b
t
STANDARD MODEL
ν mass
Brownian motion
Photon
Radio-activity
Special relativity
Quantum mechanics
Wave / particle
Fermions / Bosons
Spin
Antimatter
Fermi Beta-Decay
Yukawa π exchange
QED
P, C, CP violation
W bosons
Higgs
EW unification
GUT
SUSY
Superstrings
QCD Colour
W
Z
g
3 generations
1
2

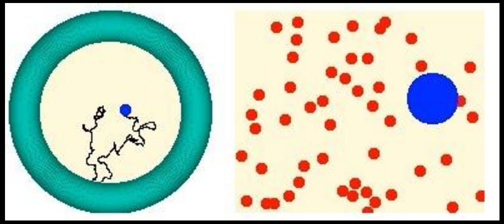
MATTER IS MADE OF PARTICLES

J.J. Thomson

1897: ELECTRON - the first ‘discrete’ building block of matter

A. Einstein

1905: ATOMS ARE REAL - Explanation of Brownian Motion (Perrin)

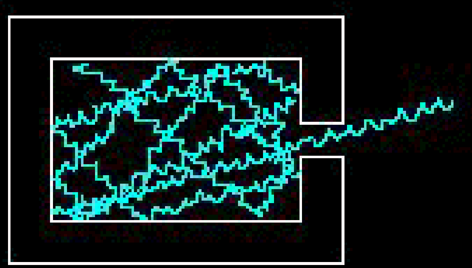


$$\langle x^2 \rangle = \frac{2kTt}{\alpha} = \frac{kTt}{3\pi\eta a}$$

ENERGY COMES IN QUANTA

M. Planck

1900: ELECTROMAGNETIC RADIATION IS EMITTED IN QUANTA



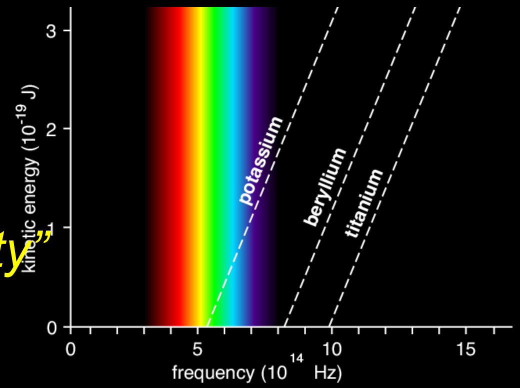
$$\varepsilon = h\nu$$

$$I(\nu) \sim \nu^2 \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$$

P. von Lenard

1902: PHOTOELECTRIC EFFECT

"The electron energy does not show the slightest dependence on the light intensity"



A. Einstein

1905: LIGHT IS EMITTED AND ABSORBED IN QUANTA

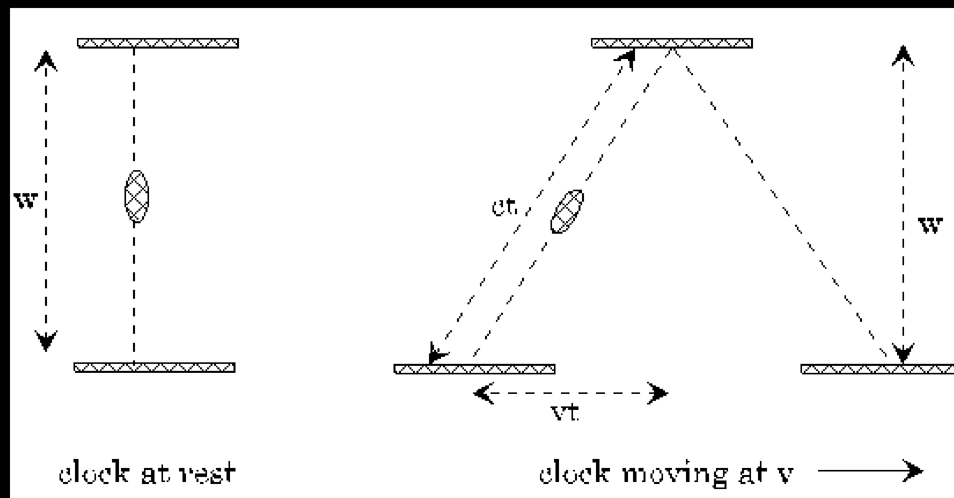
$$E_{max} = h\nu - W$$

"My only revolutionary contribution to physics"

SPECIAL RELATIVITY

A. Einstein

1905: SPEED OF LIGHT IS ALWAYS CONSTANT



$$c^2t^2 = v^2t^2 + w^2$$

$$t = \frac{w/c}{\sqrt{1-\frac{v^2}{c^2}}} = \gamma \cdot \tau$$

1) Time dilation, space contraction

2) Modification of Newton’s laws, relativistic mass increase.

$$E=mc^2$$

THE BEGINNING OF ATOMIC PHYSICS

Rutherford

1909: NUCLEI: very small + heavy within (almost) empty atom

Hydrogen

1913: BOHR MODEL- (empirical) explanation of discrete spectral lines

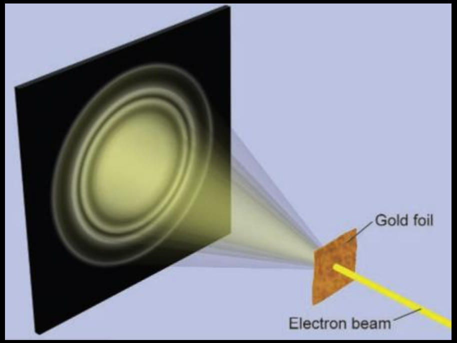
(using Planck's constant h) to quantize angular momentum

L. de Broglie

1923: DE BROGLIE

Particles are waves

$$\lambda = \frac{h}{p}$$

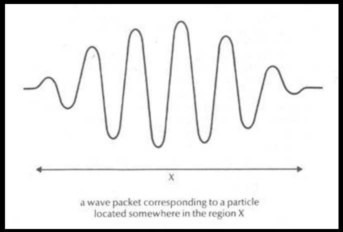


QUANTUM MECHANICS

Heisenberg

1923: UNCERTAINTY RELATION

$$\Delta x \Delta p \geq \frac{\hbar}{2} \qquad \Delta E \Delta t \geq \hbar$$

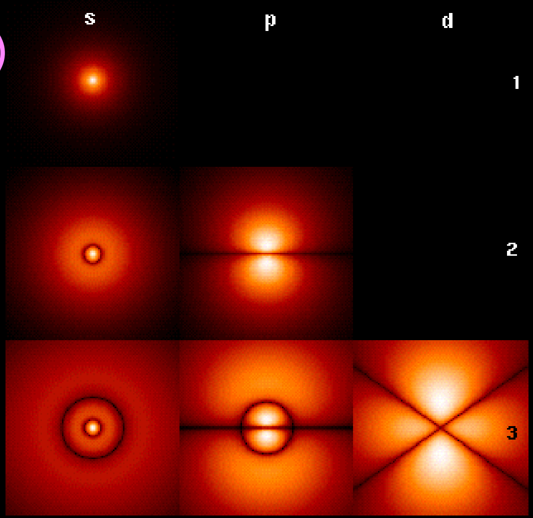


Schrödinger

1926: SCHRÖDINGER EQUATION

$$H\psi(\mathbf{r},t) = (T+V)\,\psi(\mathbf{r},t) = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r})\right]\psi(\mathbf{r},t) = i\hbar\frac{\partial\psi}{\partial t}(\mathbf{r},t)$$

(electrons in atoms form ‘standing waves’)



Interpretation (Born, 1927):

ψ = probability amplitude

$|\psi|^2$ = probability

RELATIVISTIC QUANTUM MECHANICS

Paul A.M. Dirac
(1928)

$$E^2 = p^2 + m^2 \rightarrow$$

$$E = \pm(\alpha \cdot p) + \beta m$$

$$(i\gamma^\mu \partial_\mu - m)\Psi = 0$$

$$\Psi = \begin{pmatrix} e^- \uparrow \\ e^- \downarrow \\ e^+ \uparrow \\ e^+ \downarrow \end{pmatrix}$$

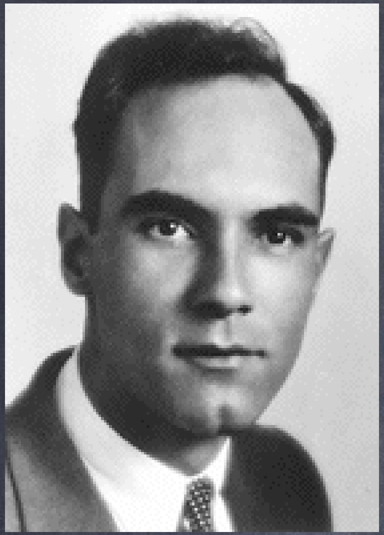
Spin

Antimatter

CONSEQUENCES:

ELECTRON SPIN EXPLAINED
ANTIPARTICLES MUST EXIST !
ELECTRONS OBEY ‘PAULI PRINCIPLE’ (1940) - FERMIONS

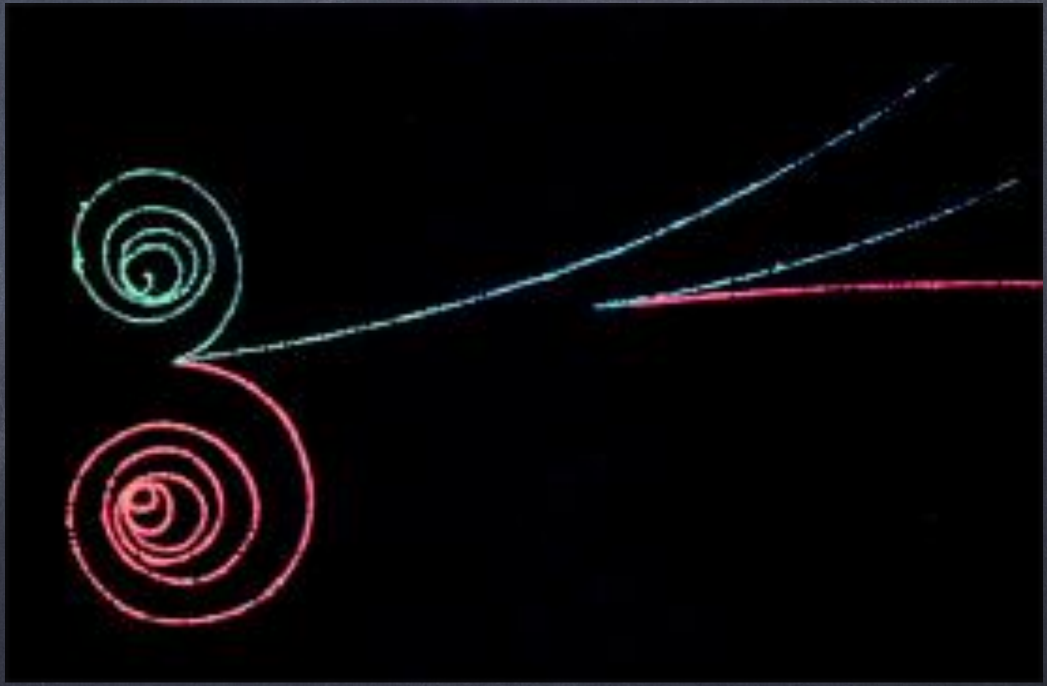
ANTIPARTICLES



Anderson

1932: POSITRON DISCOVERY

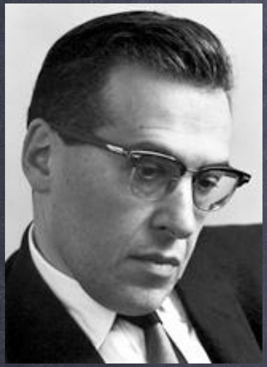
EVERY PARTICLE HAS AN ANTIPARTICLE



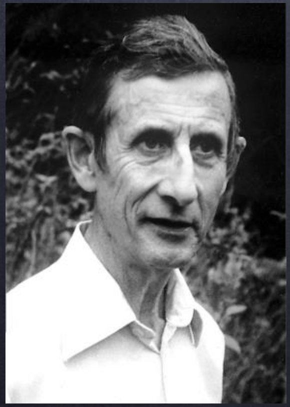
WHEN ENERGY CONVERTS TO MASS,
PARTICLES AND ANTIPARTICLES ARE PRODUCED

QUANTUM FIELD THEORY (1927 - 1948)

S.I. Tomonaga



J. Schwinger



F. Dyson

It was known that the electromagnetic field consists of photons

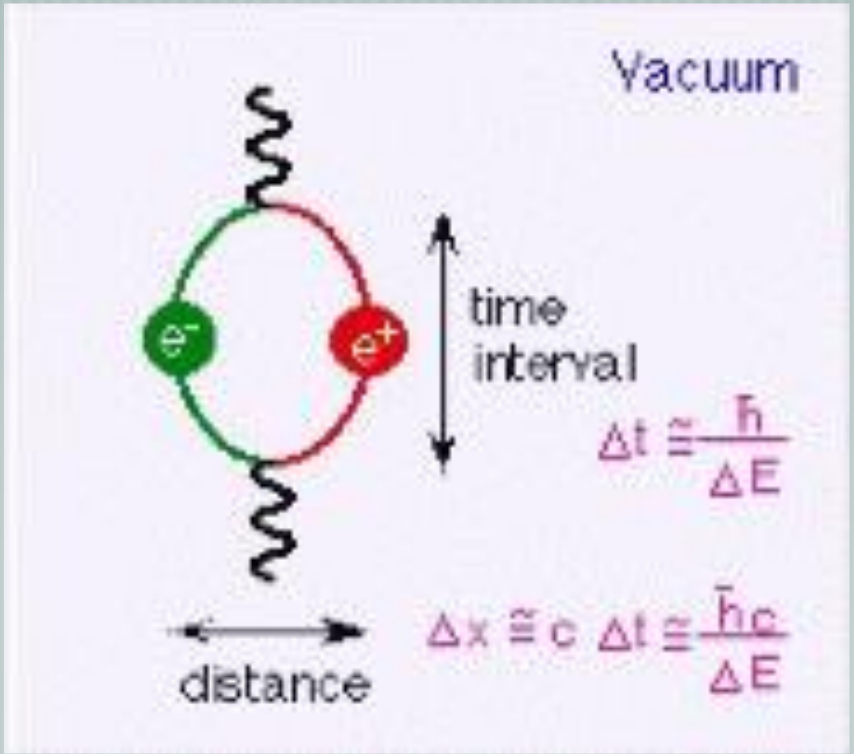
How could the interaction between electrons and photons be correctly described, respecting quantum mechanics and special relativity?

Many people worked on this problem ...

EMPTY SPACE HAD BECOME COMPLICATED !

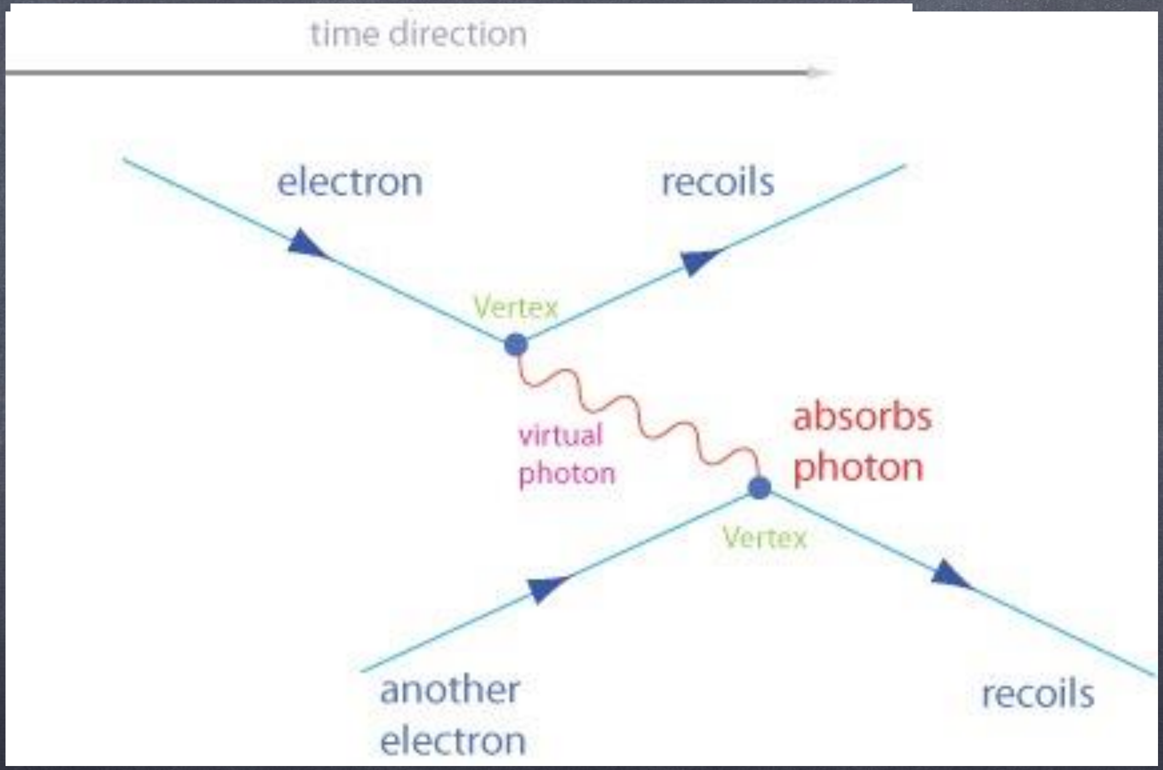
Quantum physics says that ‘oscillators’ (e.g. field quanta) cannot be at absolute rest (uncertainty relation)

The lowest energy states of e.g. electromagnetic fields can produce (virtual) electron-positron pairs: VACUUM FLUCTUATIONS



Quantum Electrodynamics (QED)

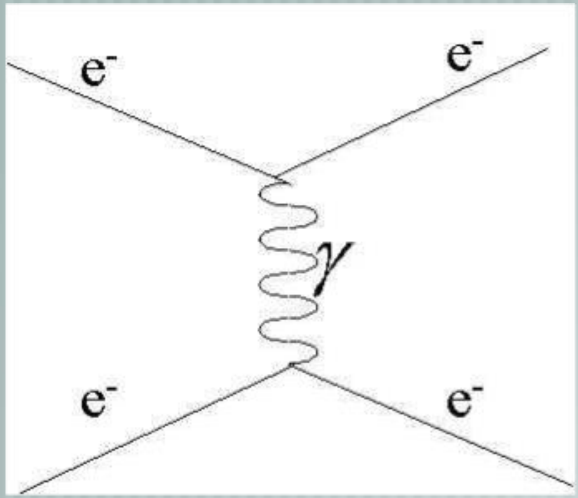
R.P. Feynman

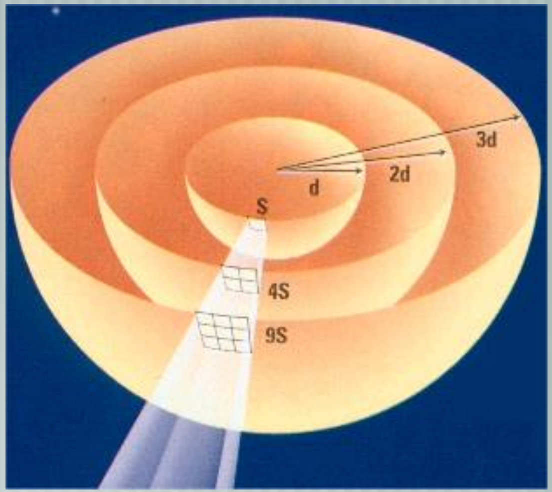


QED: Charged particles interact by exchanging photons

1) **Massless virtual photons are continuously emitted by electric charges**

2) The **$1/r^2$ law** comes from the probability to hit another particle at distance r (directly connected with the 3 dimensions of space)





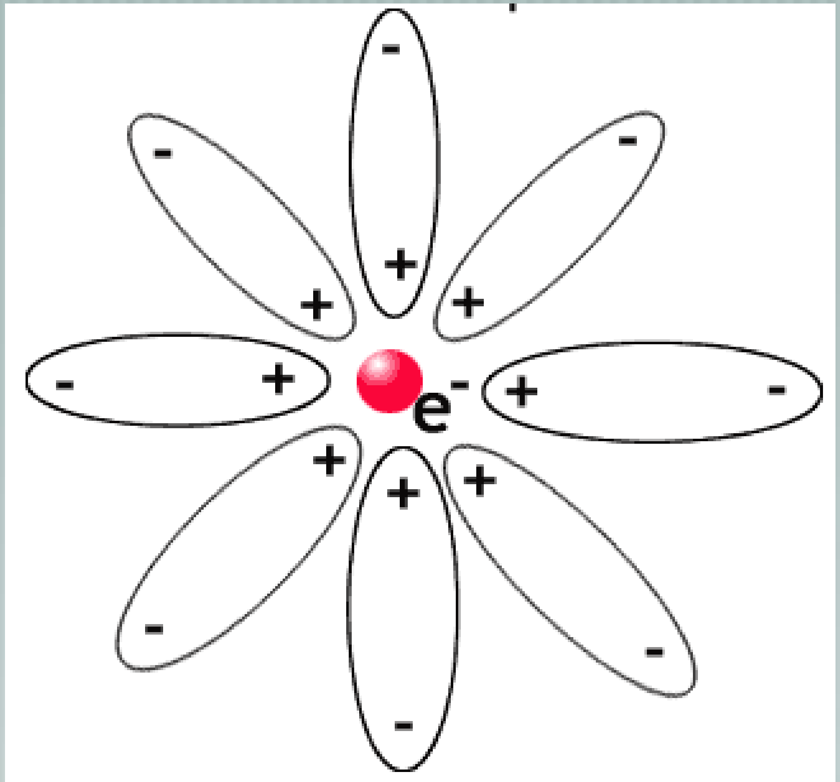
$1/r^2$ law

QED became a model for other interactions

RENORMALIZATION : HOW TO DEAL WITH INFINITIES

The ‘naked’ electron + vacuum fluctuations = measured electron

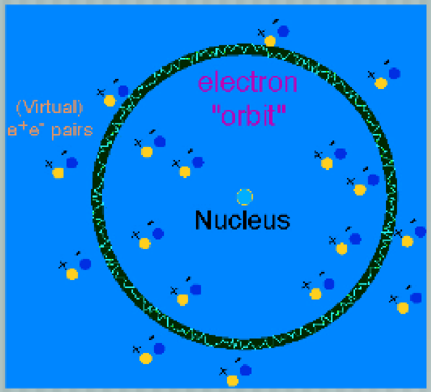
(“infinite” - “infinite” = “finite”)



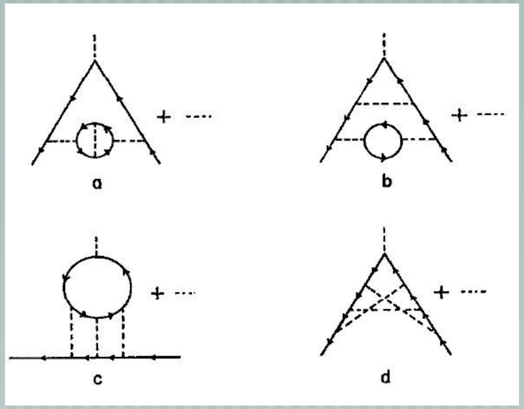
vacuum fluctuations modify its charge and mass
(‘Debye shielding’)

Vacuum fluctuations have observable effects

… and Quantum Electrodynamics allows to calculate them precisely

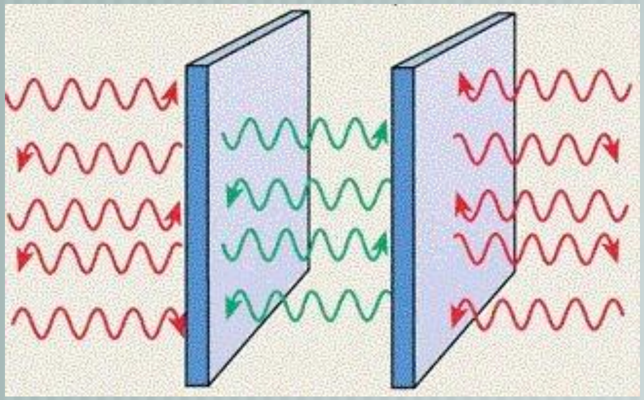


Lamb Shift
(shift of atomic energy levels)



Electron (anomalous) magnetic moment

$$\frac{1}{2}(g-2) = \frac{1}{2}\frac{\alpha}{\pi} - 0.32848\left(\frac{\alpha}{\pi}\right)^2 + (1.183 \pm 0.011)\left(\frac{\alpha}{\pi}\right)^3 .$$



Casimir effect
(force on two uncharged metal plates)

SPOOKY !

THE BEGINNING OF NUCLEAR PHYSICS

M. Curie

1895-1900: RADIOACTIVITY - strange radiation phenomena

E. Rutherford

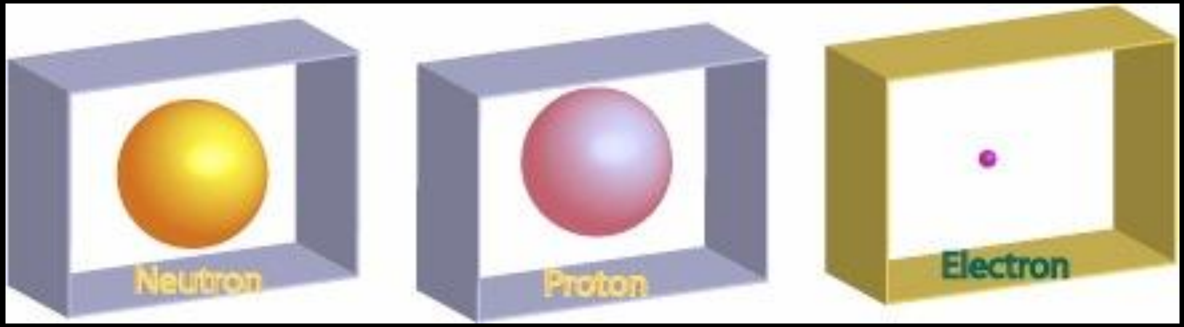
1903: Alpha-, Beta-, Gamma-Radiation known

(different penetration; Alpha = He-Nucleus)

1911: Nucleus positive, small - surrounded by electrons

J. Chadwick

1932: DISCOVERY OF THE NEUTRON



Fields

The “Strong Interaction” - Nuclear forces

Yukawa (1934)

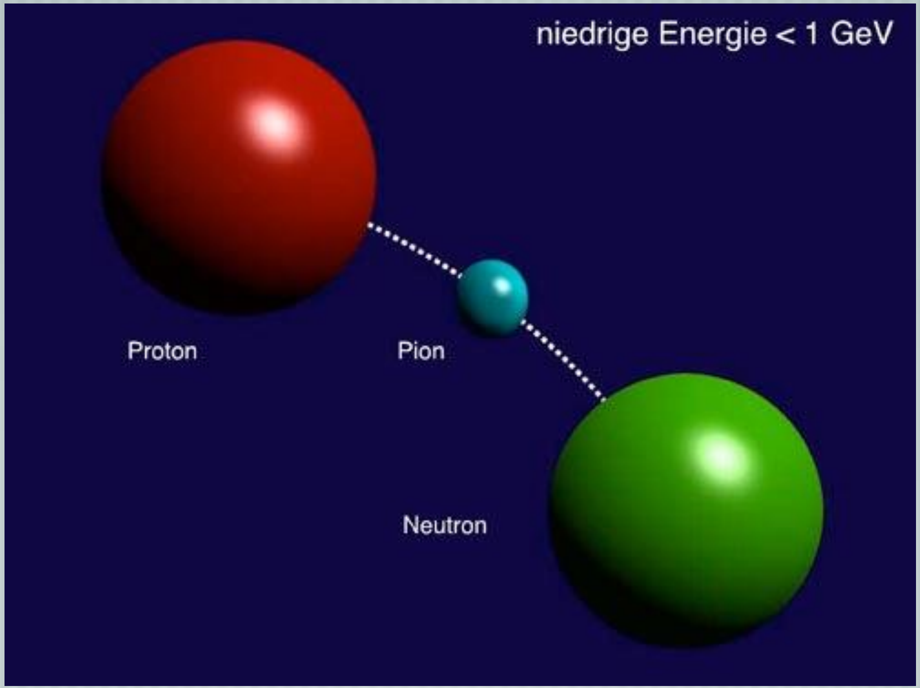
What keeps the protons and neutrons together in the nucleus?

1) This force must be stronger than the electromagnetic repulsion

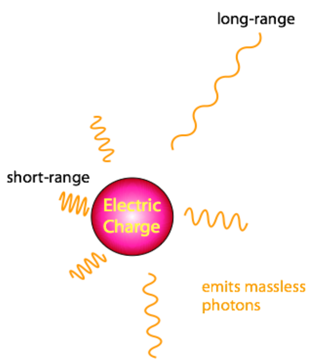
2) It must be of short range (~ 1-2 fm) to explain the size of nuclei

Yukawa’s idea:

a massive particle (“pion”) is exchanged between two nucleons



Electromagnetic vs Nuclear



$$\Delta E \, \Delta t \geq \hbar \qquad (\Delta E \sim m)$$

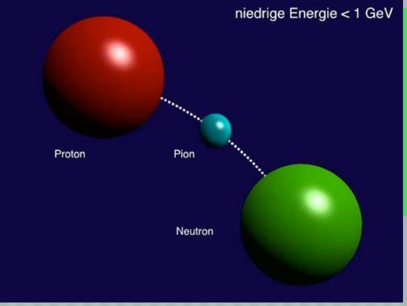
$$r = c\,\Delta t = \frac{\hbar c}{m} \sim \frac{200 \text{ MeV fm}}{m}$$

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

Coulomb law

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

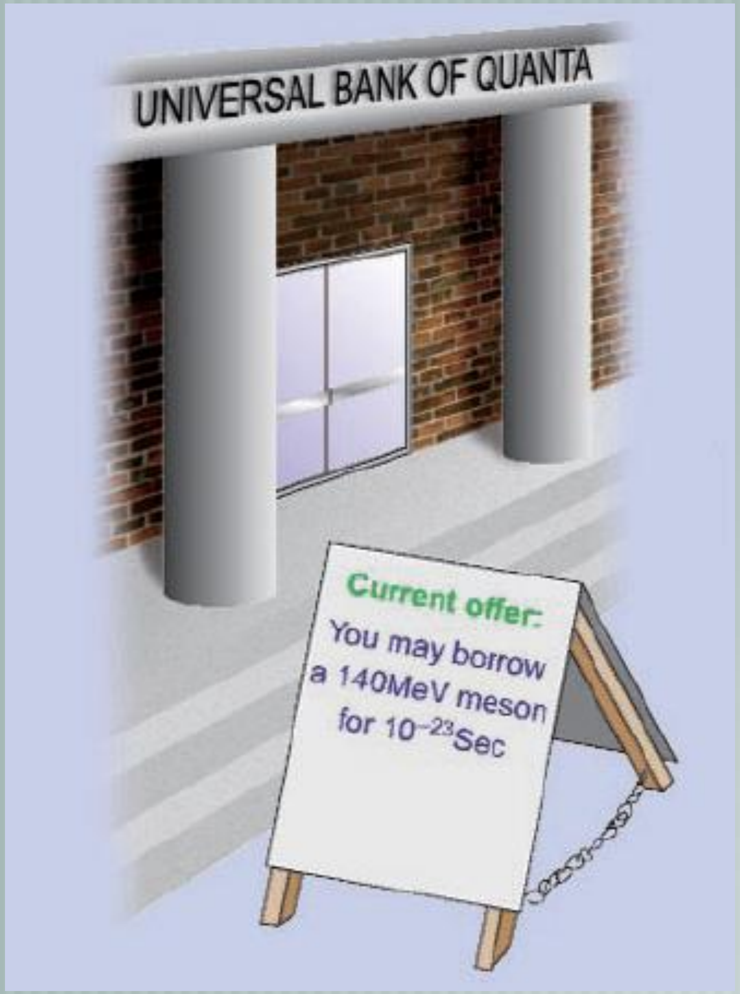
Yukawa potential ~ Modified “Coulomb” law



Fields

'Strong' interaction

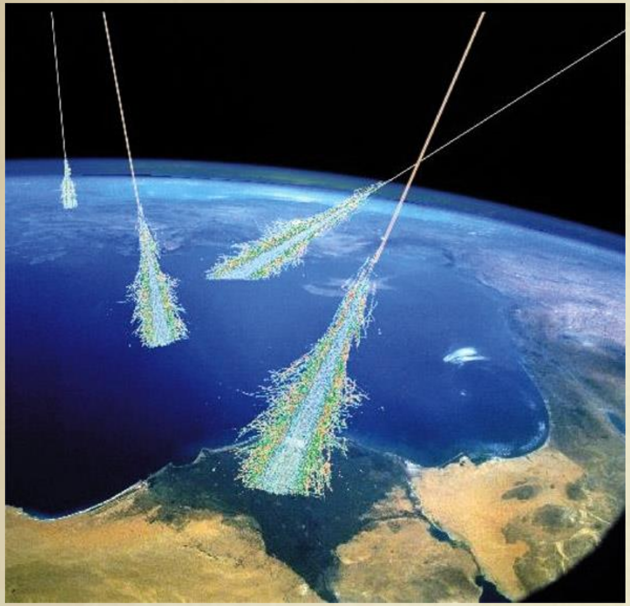
Metaphors for 'particle exchange'

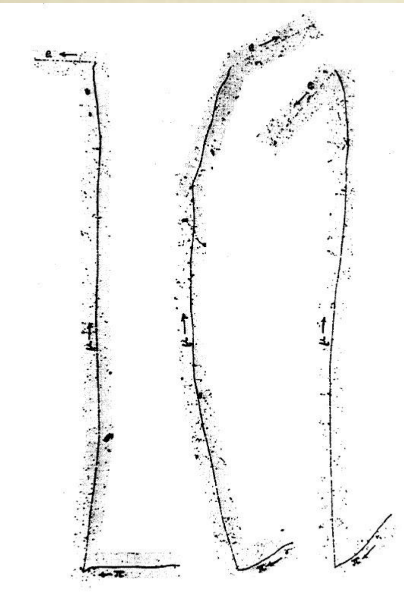


G. Gamov

Allowed by uncertainty relation: 1.4 fm ~ 140 MeV

PARTICLE SPECTRUM





1913: Cosmic Rays were discovered

Physicists went on mountain tops for experiments!

1937: Negative particle with M ~ 200 m_e

Very longe range in matter !? Not Yukawa's "pion" !

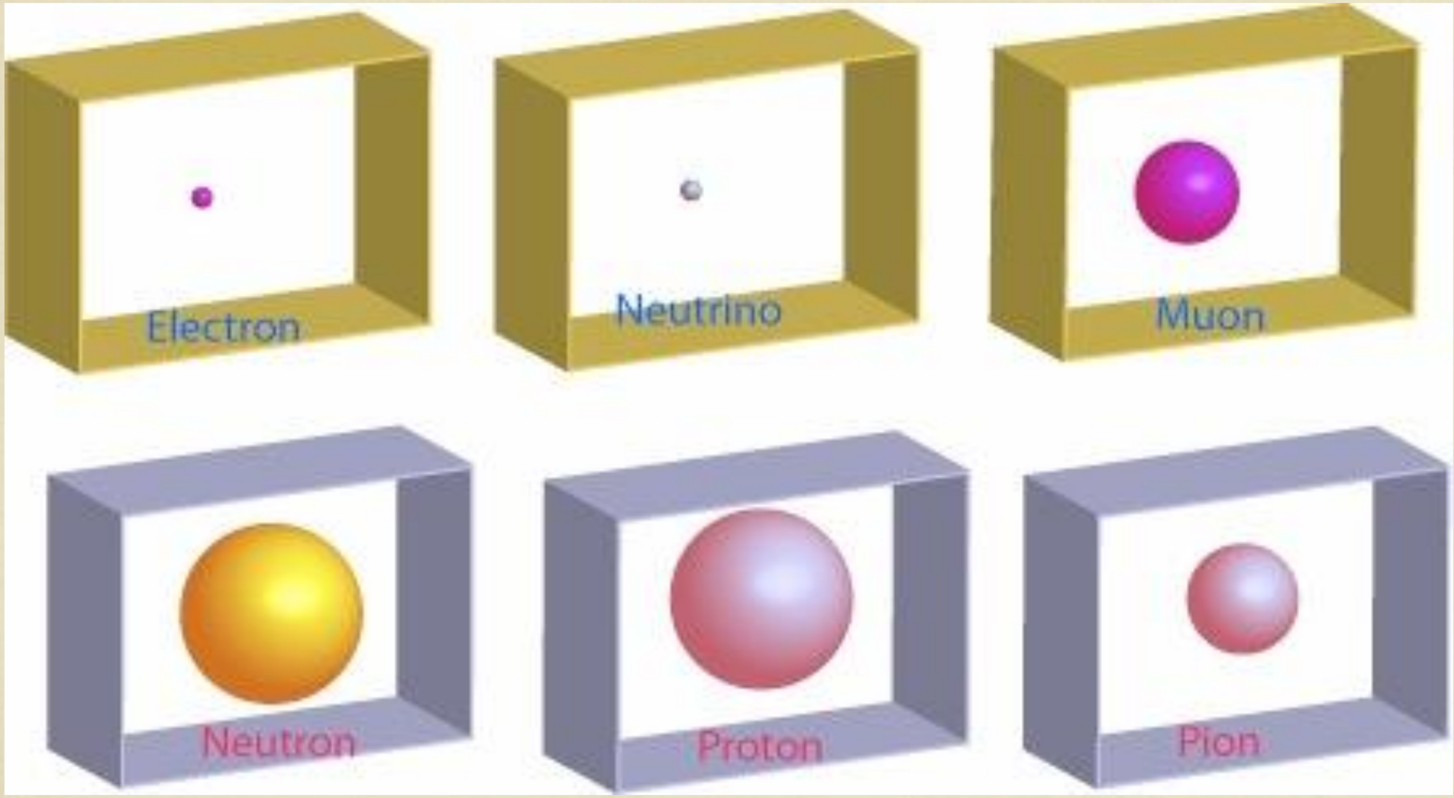
Muon = 'heavy electron'

Who ordered that ?

1948: Discovery of the 'pion'

PARTICLE SPECTRUM

In 1948, the particle spectrum started to look ugly:



PARTICLE SPECTRUM

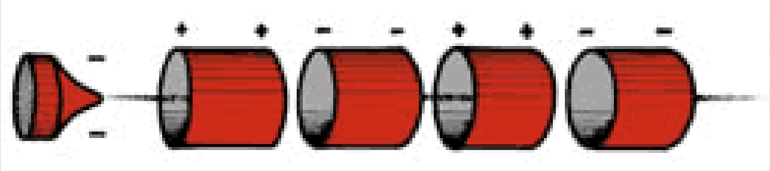
1931 - 1955

Accelerators

"Man-made cosmic rays"

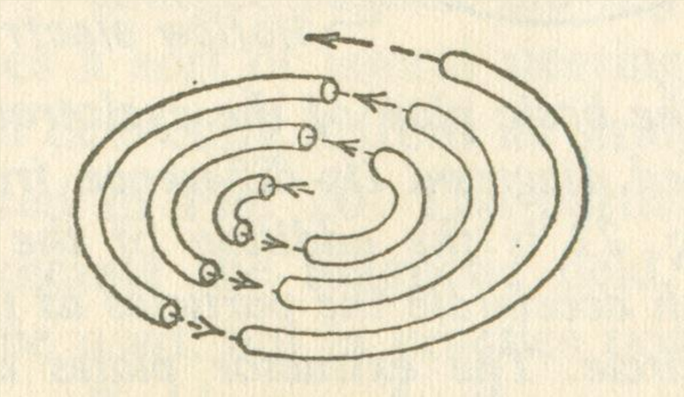
Rolf Wideroe, 1928

Ernest Lawrence, 1931



Linear accelerator

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



Cyclotron

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

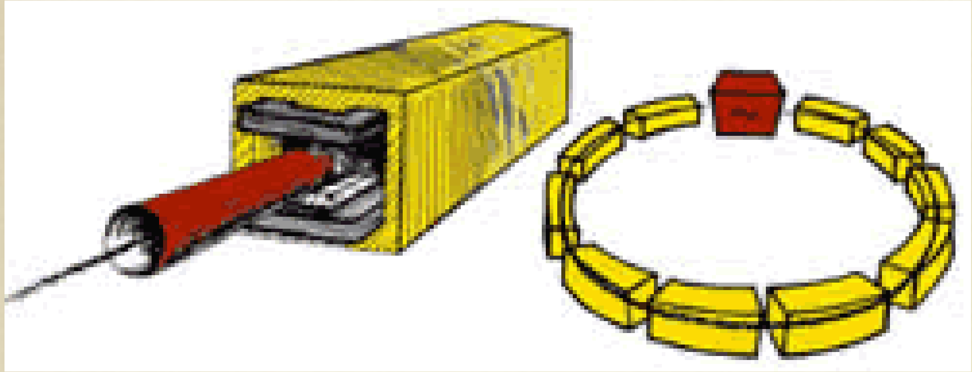
1931: 80 keV
1932: 1000 keV
1939: 19 MeV*
1946: 195 MeV ("synchrocyclotron")

* first limitations by relativistic mass increase

PARTICLE SPECTRUM

1931 - 1955

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 SPECTRUM

Particle zoo

1950- 1968

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

Mesons

π^+ π^- π^0

Pions

K^+ K^- K^0

Kaons

η'

Eta-Prime

η

Eta

φ

Phi

ρ^+ ρ^- ρ^o

Rho

BARYONS

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

Delta

Λ^0

Lambda (strange!)

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

Sigma (strange!)

Ξ^0, Ξ^-

Sigma(very strange!)

What was the underlying structure ?

PARTICLE SPECTRUM

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

Gell-Mann, 1963

(G. Zweig, 1963, CERN)

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

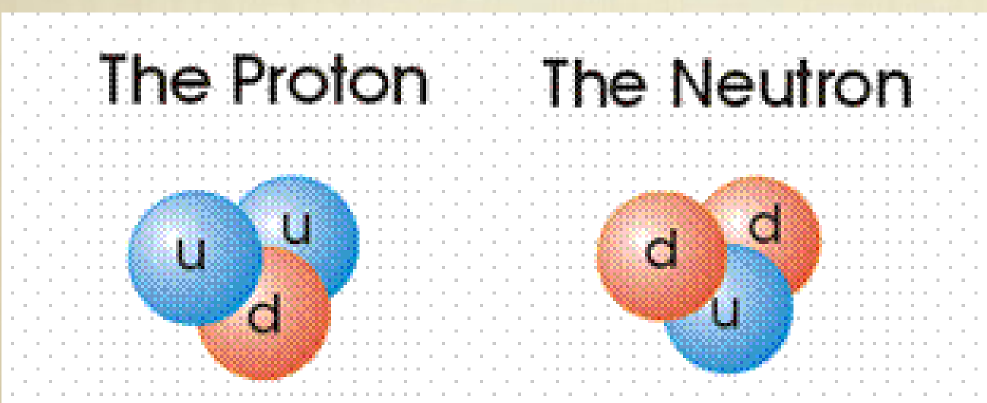
2) Carry electric charges: +2/3, -1/3, -1/3

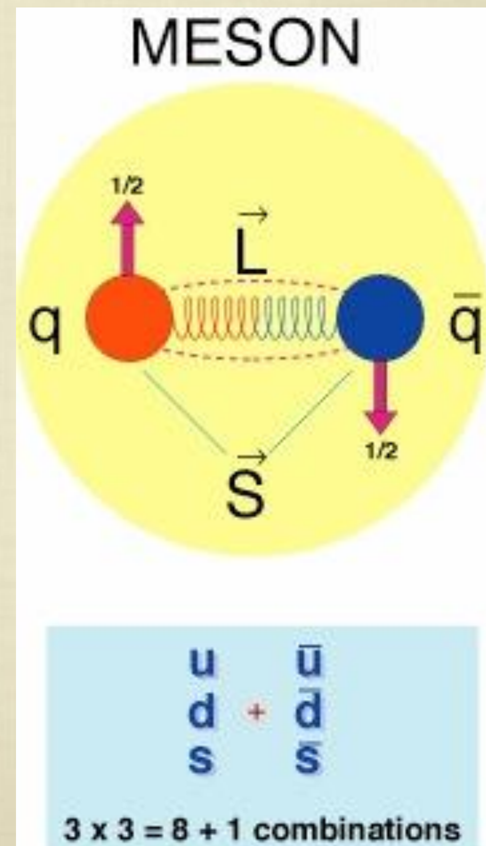
3) Appear in combinations:

Meson = quark+antiquark

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

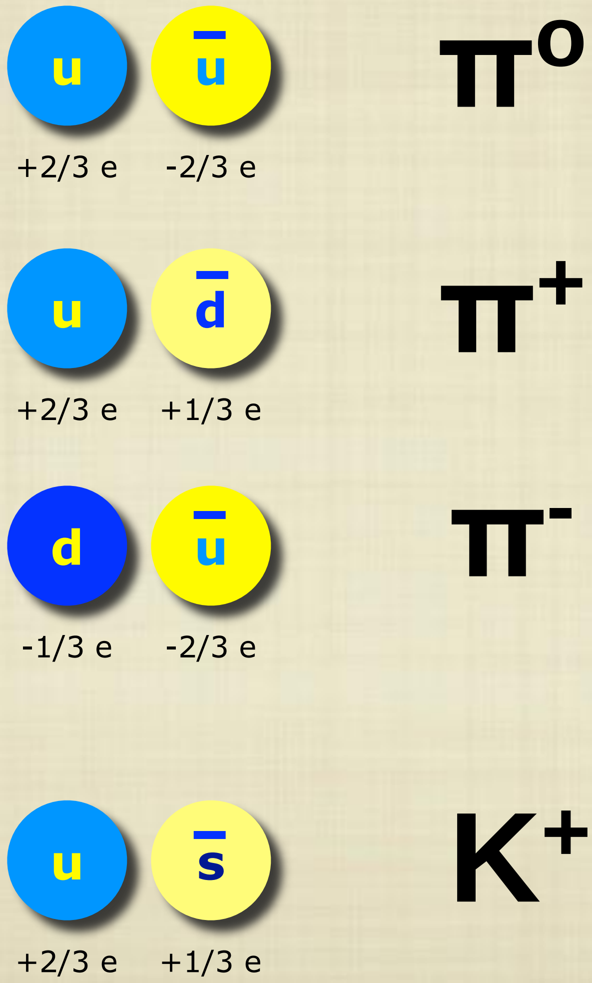
+2/3 e   -1/3 e   -1/3 e

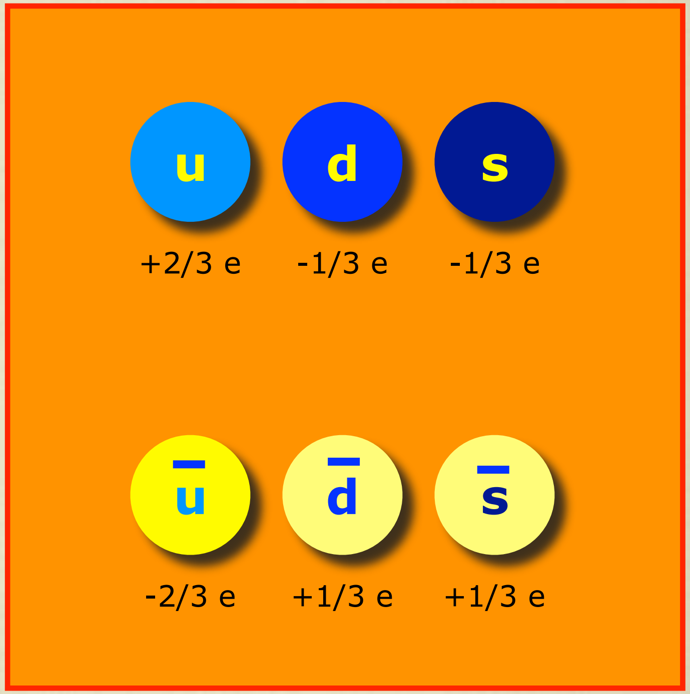




PARTICLE SPECTRUM

Some mesons (quark+antiquark):

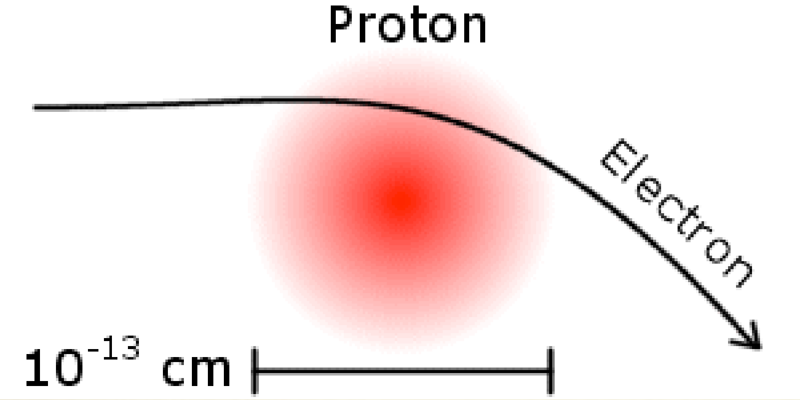




PARTICLE SPECTRUM

1967 Discovery of quarks

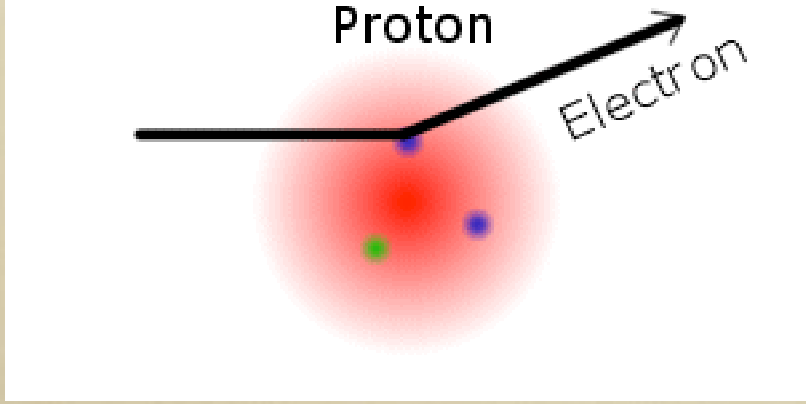
Electron-Proton scattering (1956)



1956 Hofstadter: measured finite proton radius

Stanford Linear Accelerator Centre

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



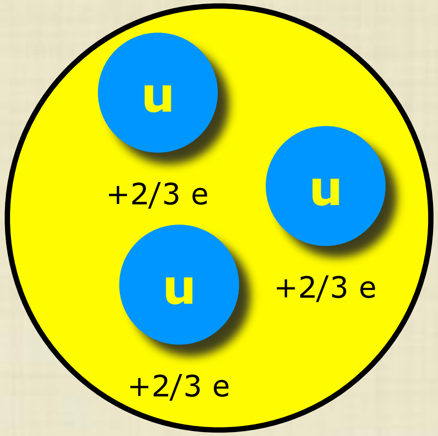
Measured cross-sections perfectly compatible with presence of 2 up- and 1 down-quark in proton

1973

The concept of “Colour” charge

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

Δ^{++}



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, Fritzsch, Gell-Mann)

PARTICLE SPECTRUM

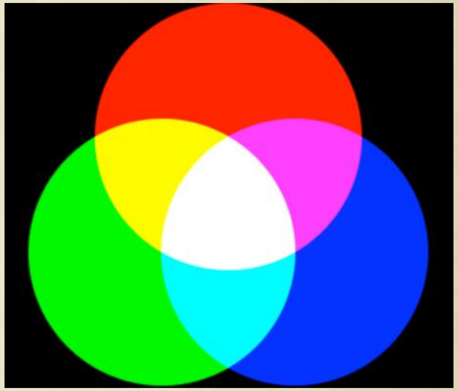
this has nothing to do with our visible colours, just an analogy

Quantum **C**hromo **D**ynamics

Theory constructed in analogy to QED

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

‘Strong force’ between quarks is transmitted by (8) gluons



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

MESONS = Quark-Antiquark

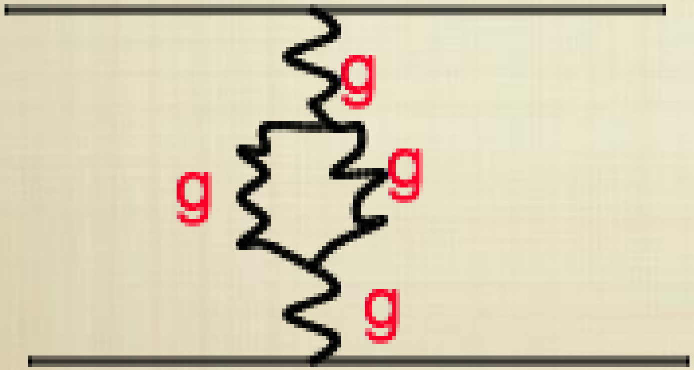
BARYONS = 3-Quark states

PARTICLE SPECTRUM

1973

GLUONS CARRY COLOUR CHARGE : SELF-INTERACTION !

At low energies, QCD long-range forces increase with distance. These forces keep the quarks as ‘prisoners’.

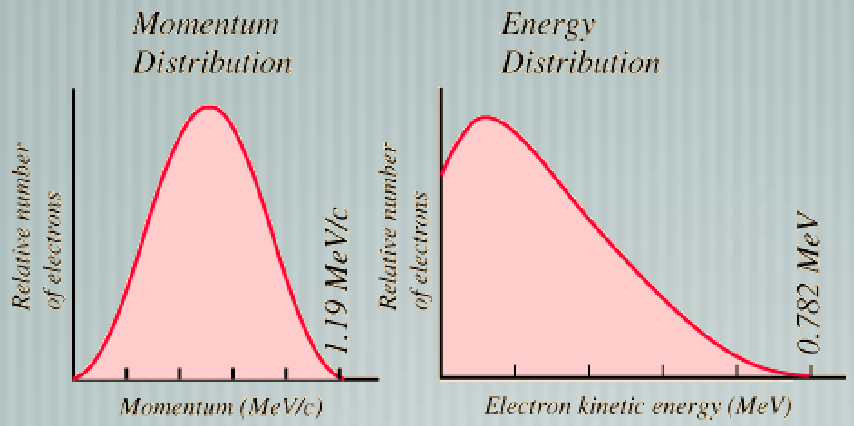


At high energies, for small distances, the force decreases: asymptotic freedom of quarks (phenomenon: the quark-gluon plasma)

The "Weak Interaction" - What is Radioactivity ?

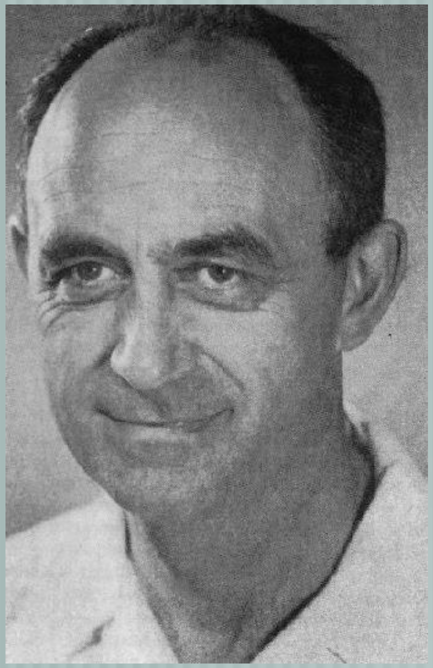
1911: Continuous (?) energy spectrum of 'beta'-rays (electrons) - energy conservation?

Z --> (Z+1) + e ?

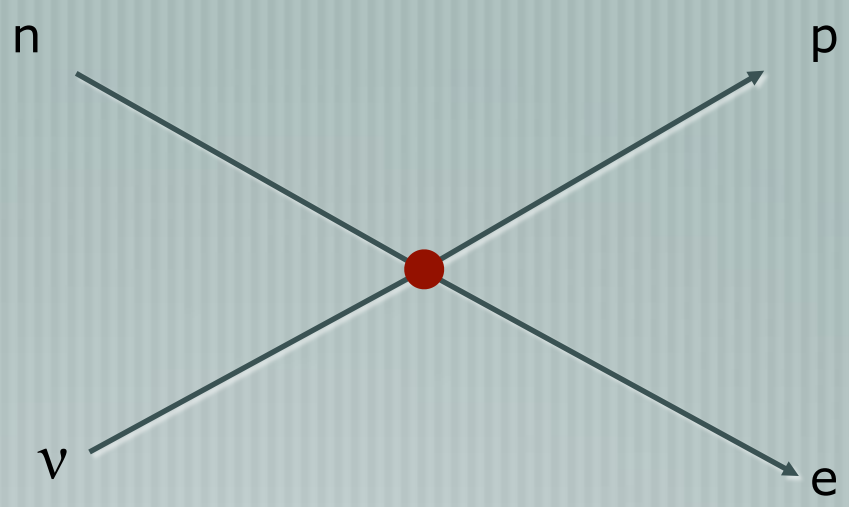


1930: Wolfgang Pauli postulates existence of 'neutrino': **n --> p + e + ν**

The model of Enrico Fermi : “pointlike interaction”



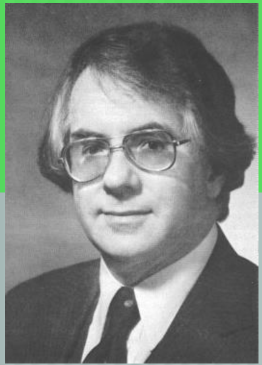
Enrico Fermi
(1934)



Proposed a **phenomenological** model of weak interaction

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

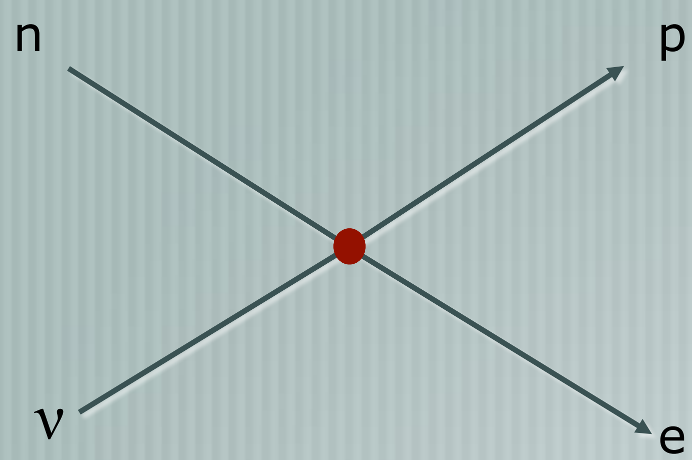
Coupling of two ‘currents’ (proton-neutron / electron-neutrino)



S. Glashow

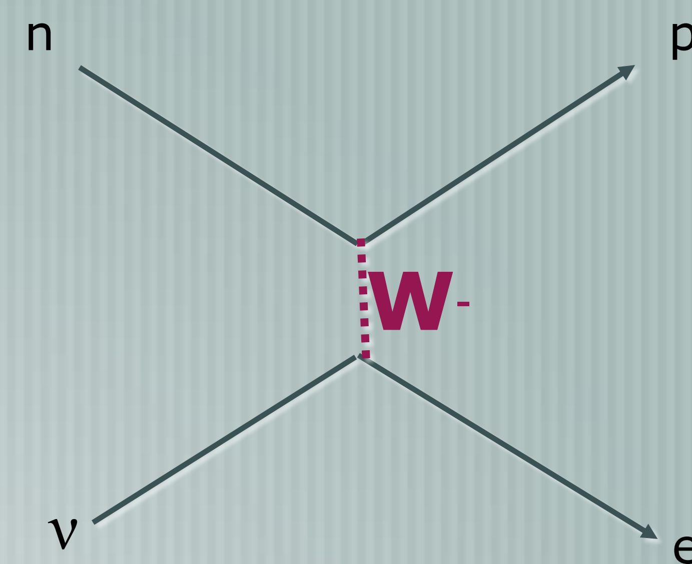
Fermi's model turned out to be inconsistent at E > 300 GeV

probability of this reaction > 100% (E > 300 GeV)



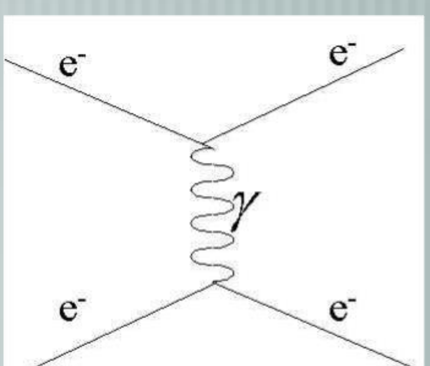
Fermi model

New Idea (1958)

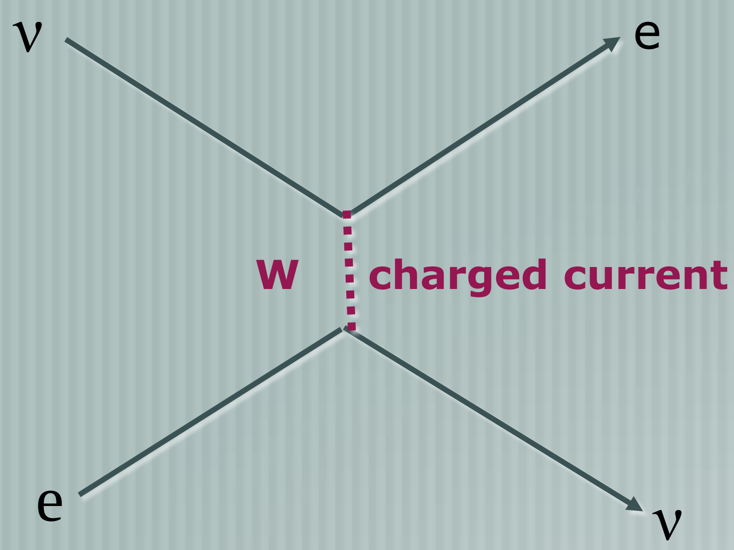


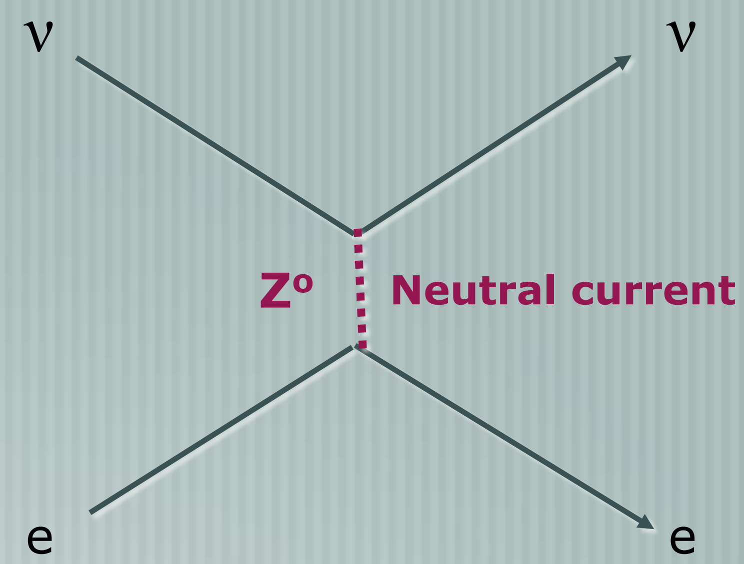
Weak interaction transmitted by massive vector bosons (in analogy to photon exchange!)

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



Unification of electromagnetic and weak interaction



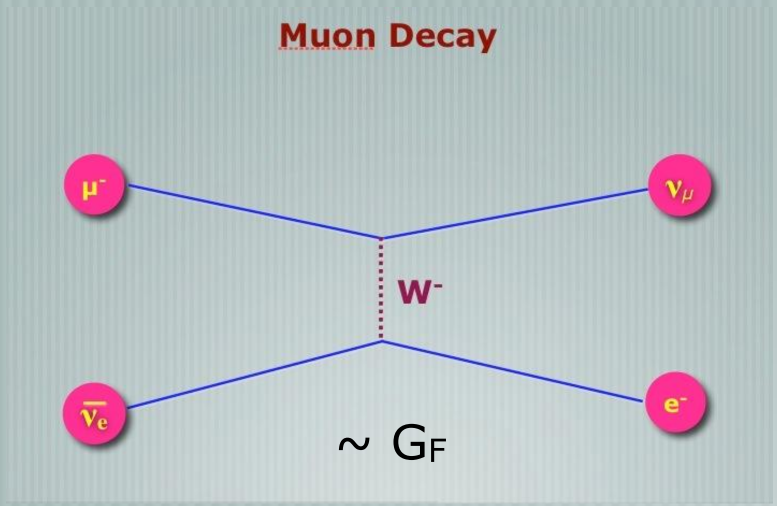


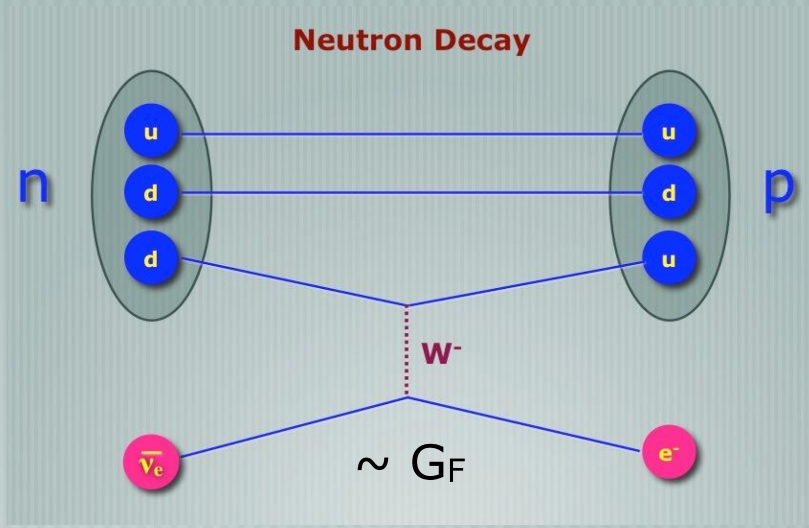
Glashow, Salam, Weinberg (1968) - Electroweak Force

- 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^o) 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)**

Fields

Electroweak interaction is the SAME for leptons and quarks





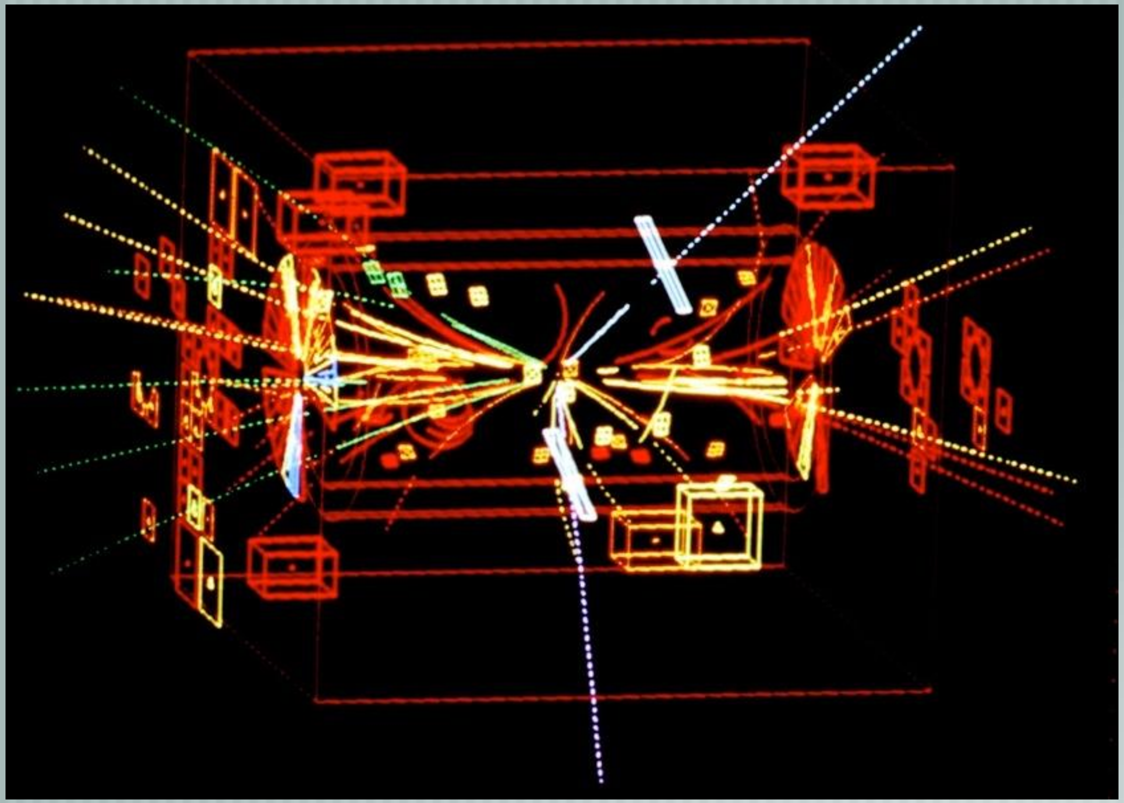
"Universality*" - transmitted by W, Z bosons, same strength!

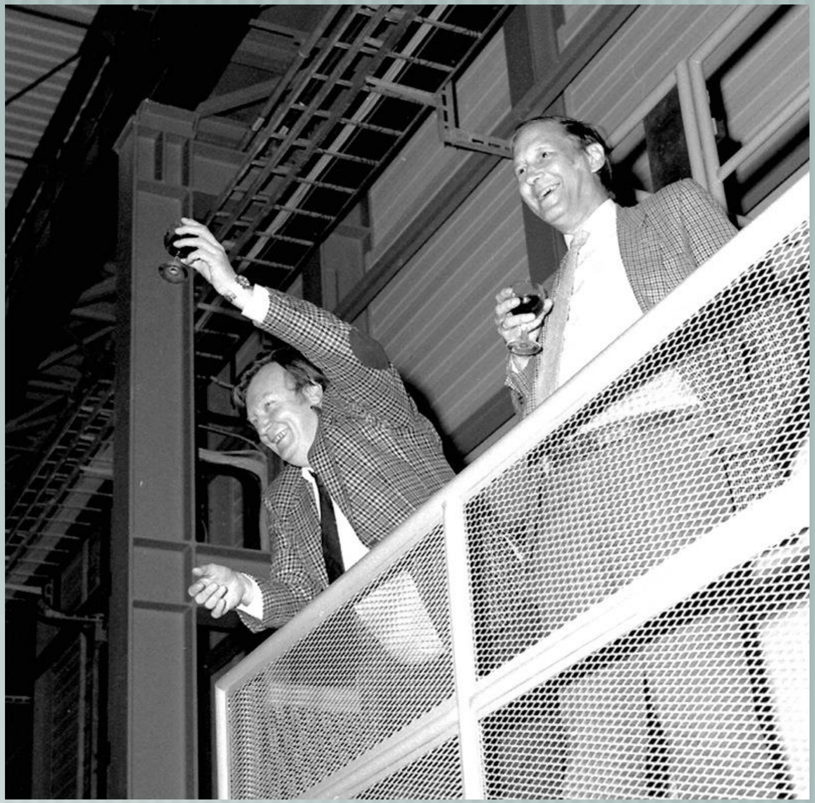
*Assuming a little bit of 'quark' mixing

$$d' = d \cos \theta_c + s \sin \theta_c$$
$$s' = -d \sin \theta_c + s \cos \theta_c$$

θ_c = Cabbibo angle ~ 20°

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





(C. Rubbia, S. van der Meer)

Approaching the 'Standard Model' of today

A legendary paper, predicting a new quark (Glashow, Iliopoulos, Maiani)

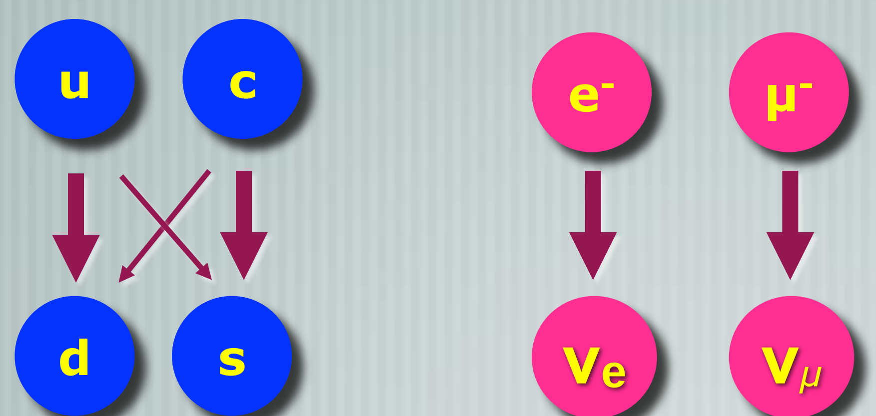
PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

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-Milis theory is discussed.

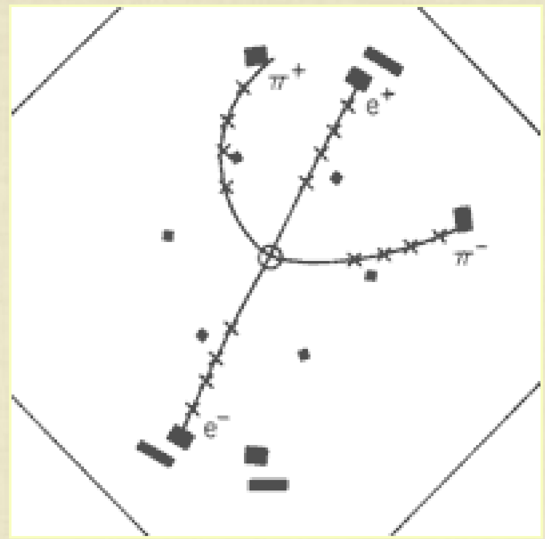
Quarks Leptons



The "Standard Model" of 1970

Discovery of the ‘charm’ quark in 1974

NOVEMBER REVOLUTION (11 November 1974)



'Psi' am SLAC (Burt Richter)
'**J**' at Brookhaven (Sam Ting)
Compromise: J/Psi

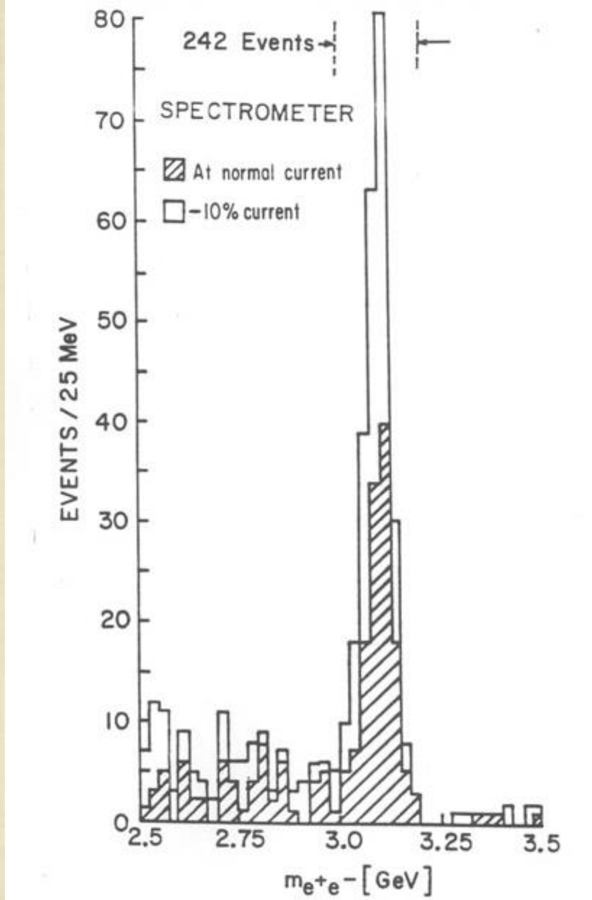
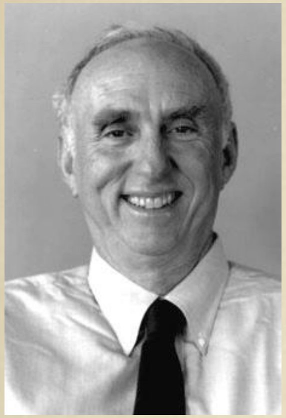


FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted wing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

“Extremely” long lifetime (~10^{-20} sec)
Decay only possible through electroweak interaction

PARTICLE SPECTRUM

But a third family of particles was going to be discovered



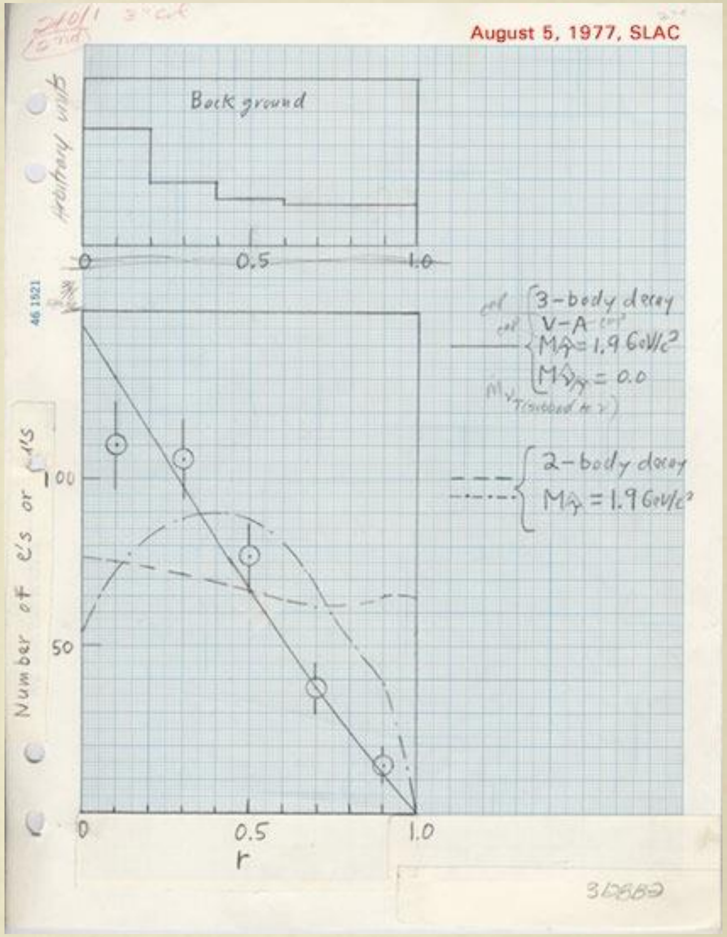
Martin Perl

A new 'heavy electron' with 3500 x m_e

... who ordered that?

THERE MUST BE A WHOLE NEW FAMILY

another neutrino (the 'tau neutrino'), and two more quarks ('top' and 'bottom')



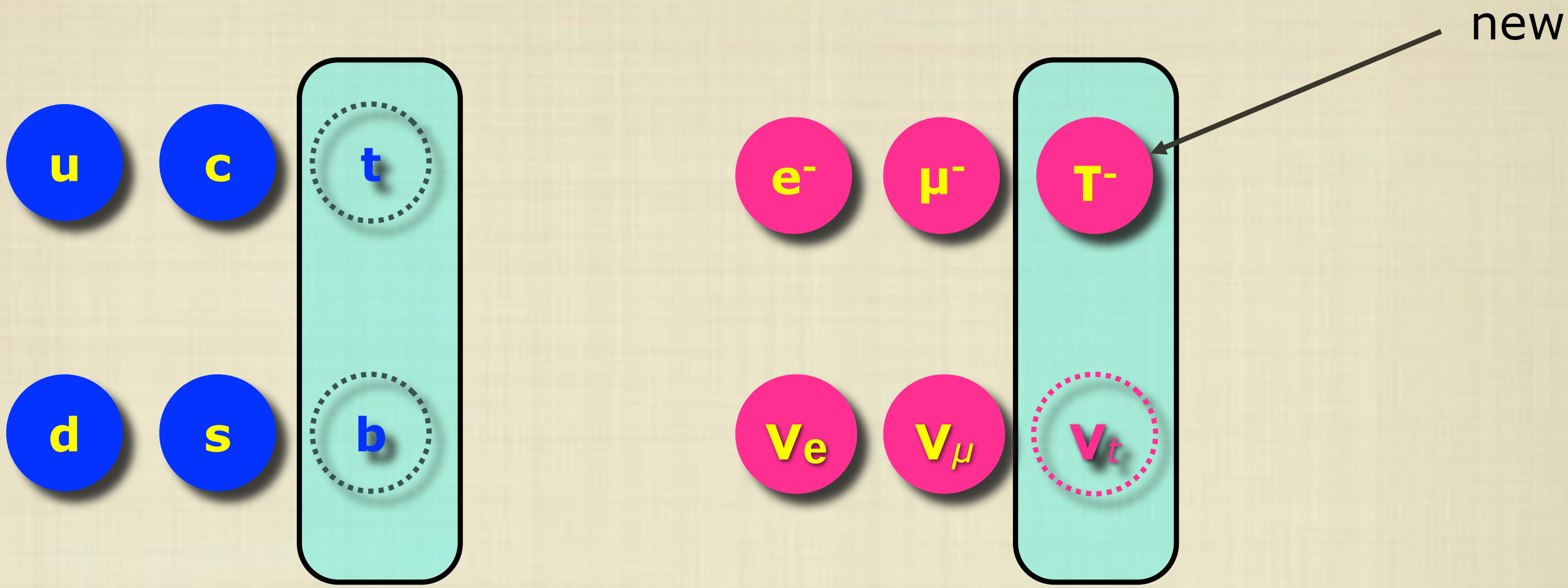
Marty Perl's logbook page

Quarks

PARTICLE SPECTRUM

1975

The search for the other family members started

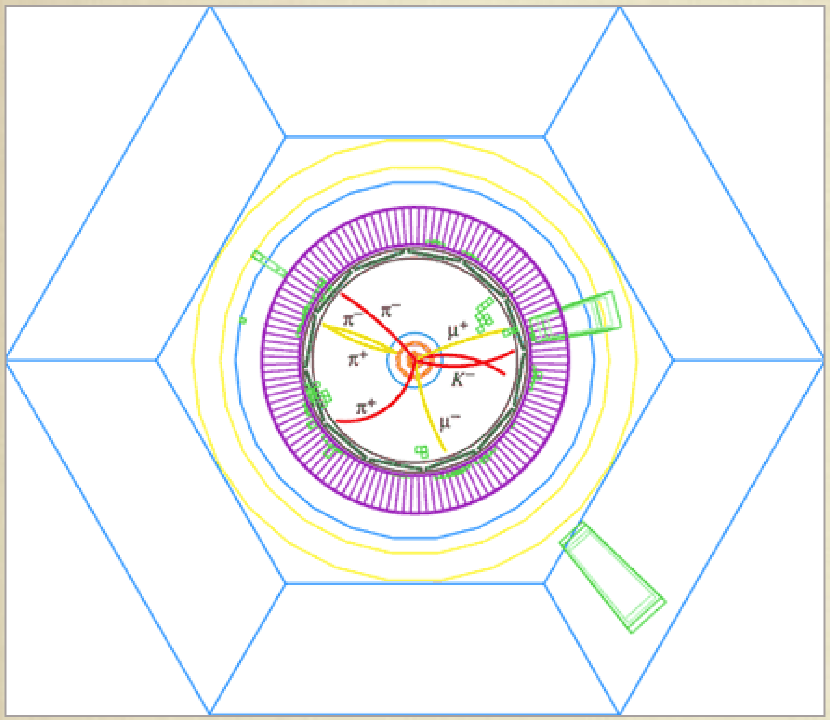


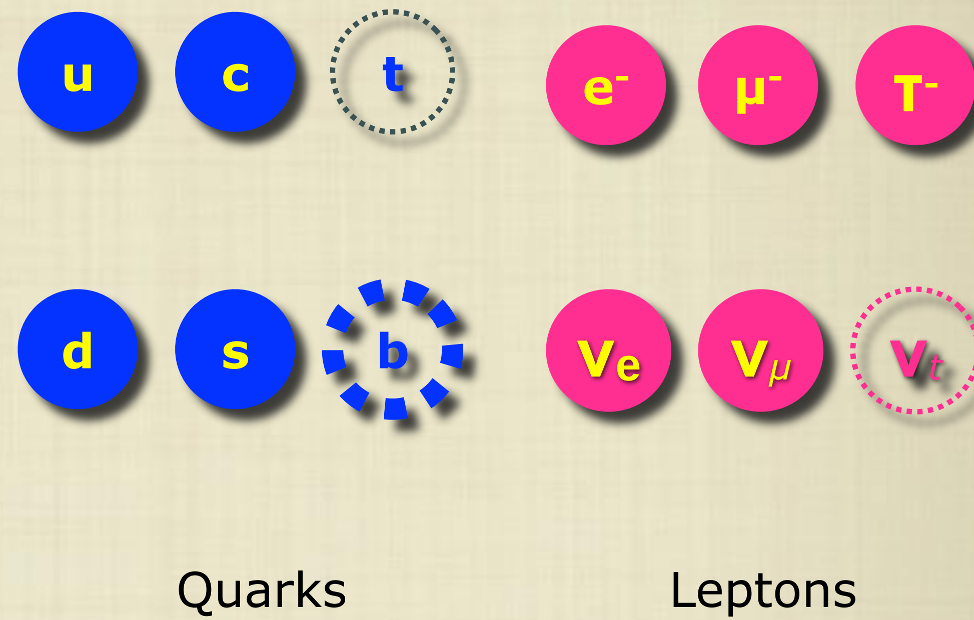
Quarks

Leptons

PARTICLE SPECTRUM

Discovery of the **'Bottom' Quark (Fermilab)**



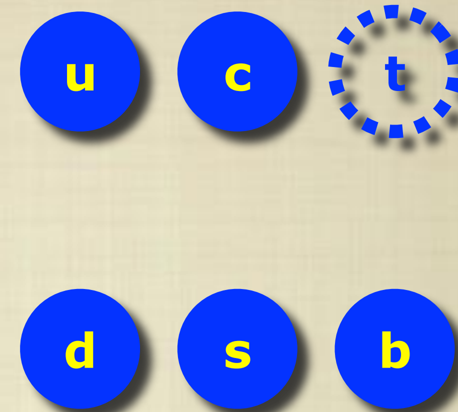


In 1977 physicists discovered a new meson called the Upsilon at the Fermi National Accelerator Laboratory.

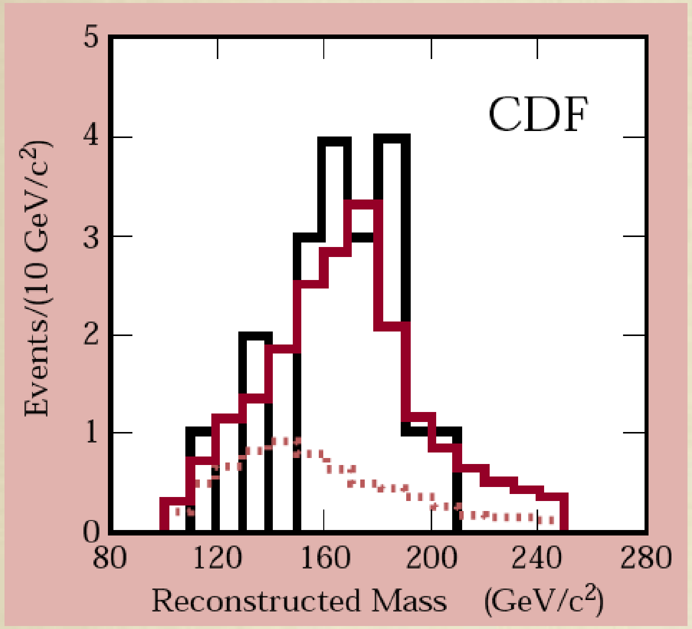
This meson was immediately recognized as being composed of a bottom/anti-bottom quark pair.

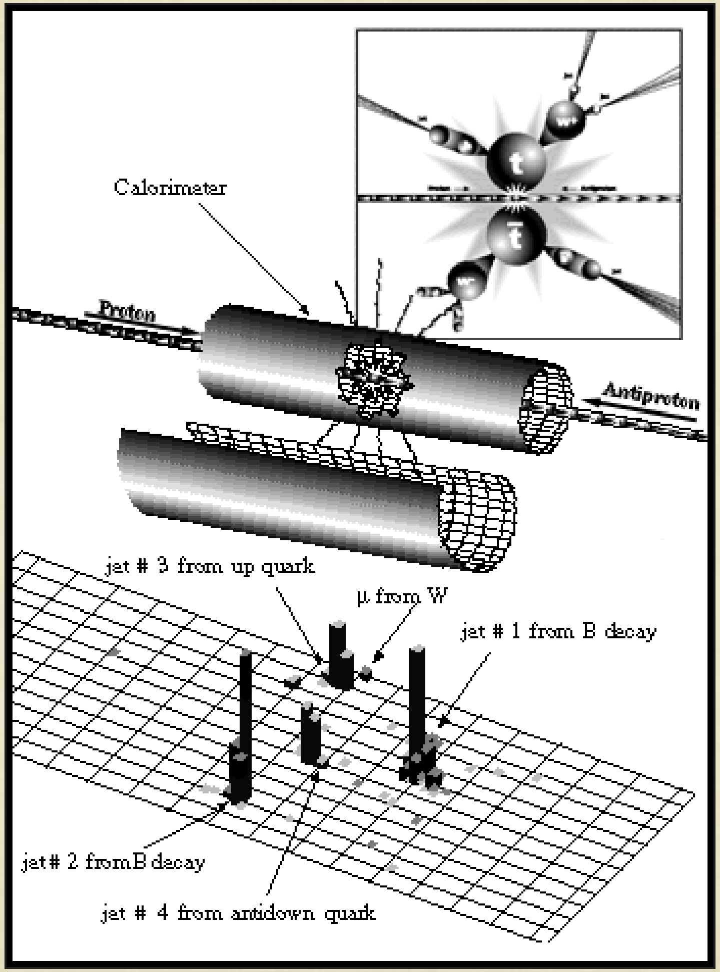
The bottom quark had charge -1/3 and a mass of roughly 5 GeV.

PARTICLE SPECTRUM



Discovery of the **'Top' Quark (Fermilab)**



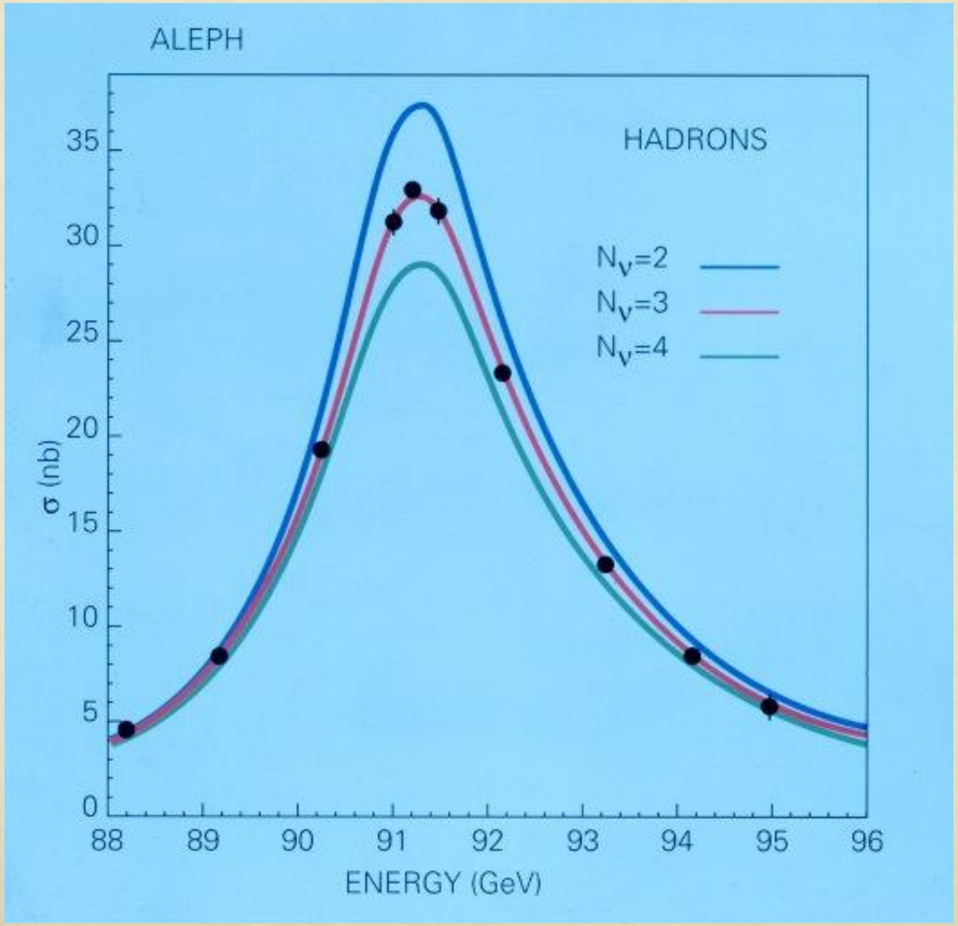


Quarks

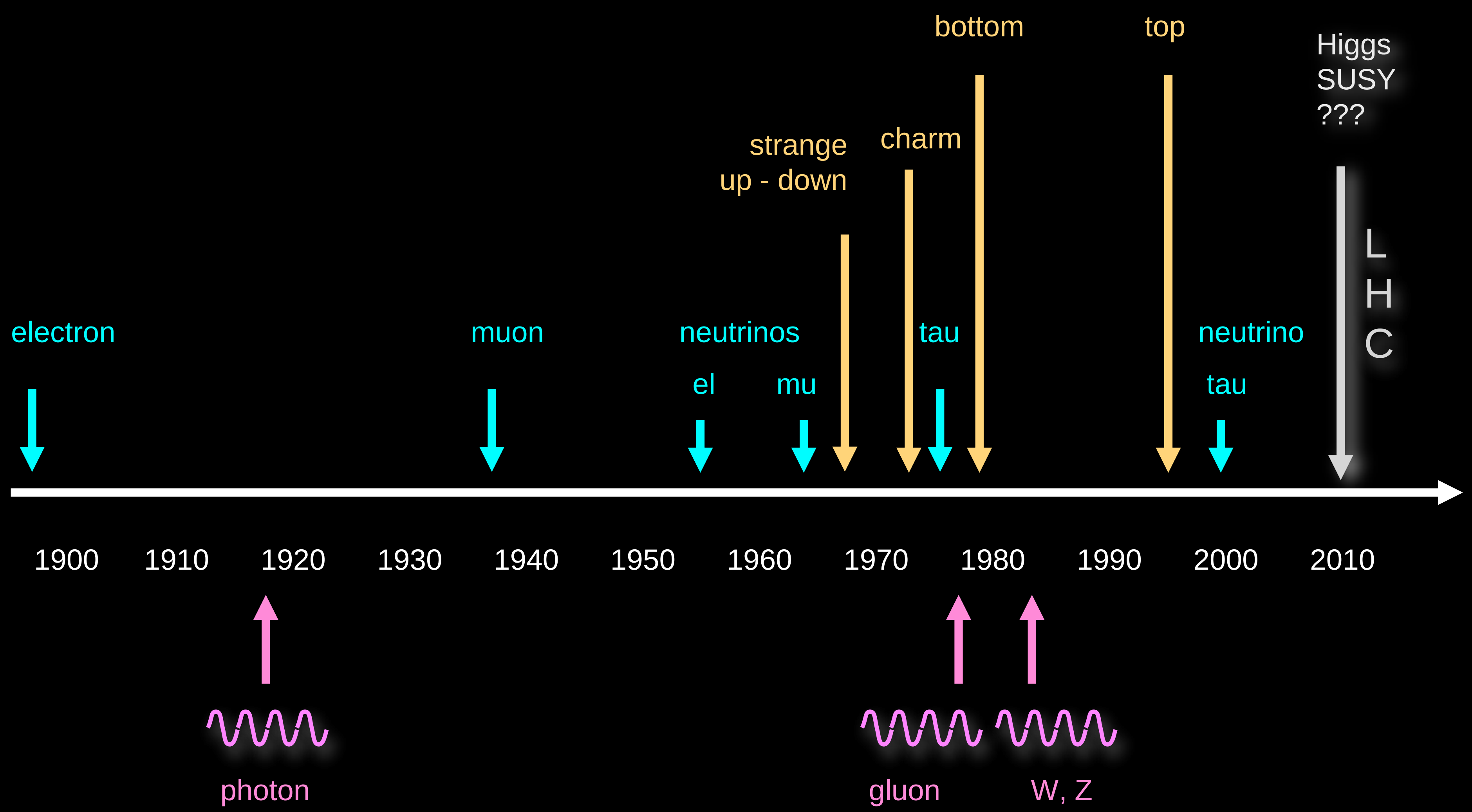
PARTICLE SPECTRUM

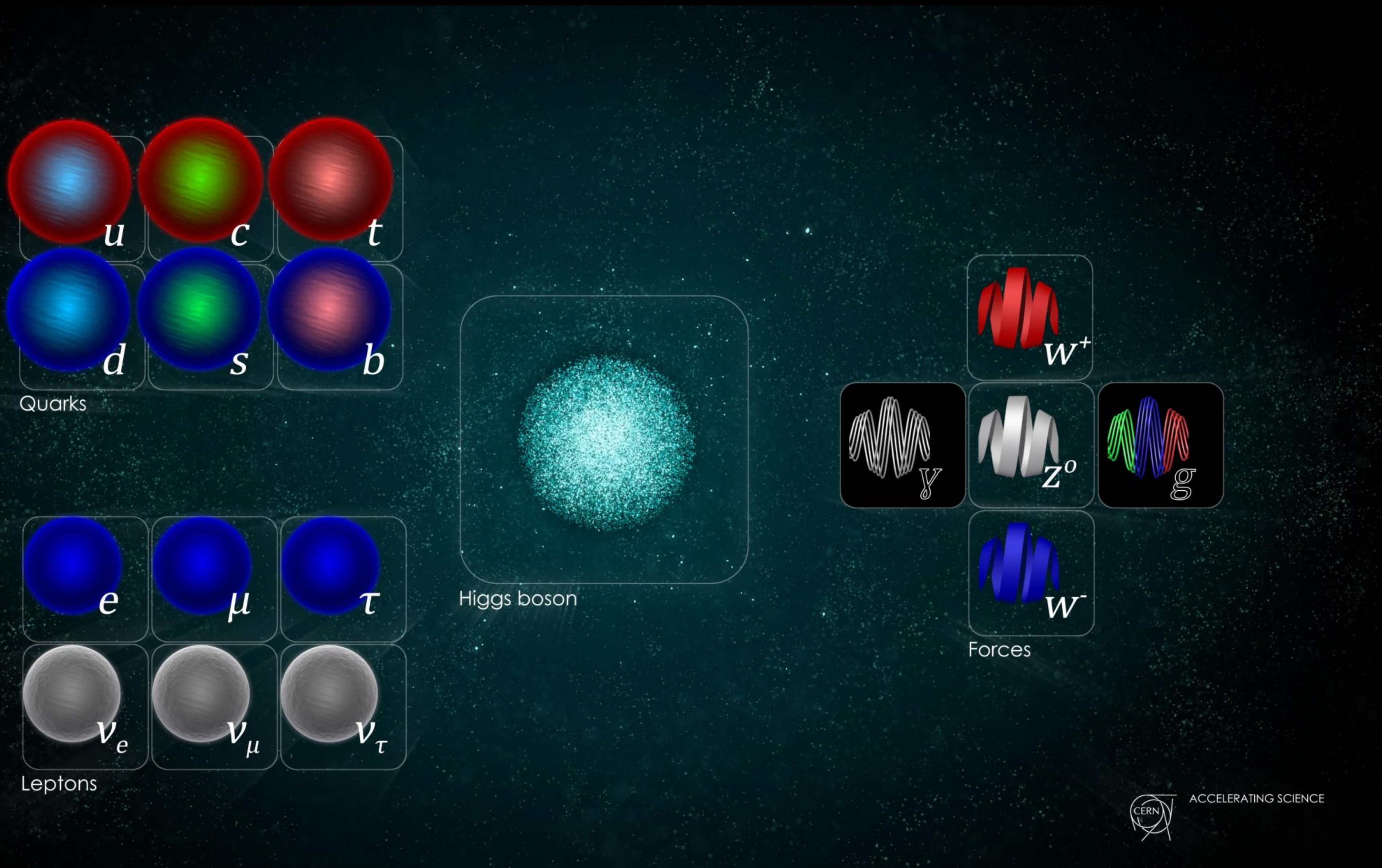
EXACTLY 3 families of particles

LEP measures the decay width of the Z^o particle



Experiments at accelerators have discovered the whole set of fundamental particles

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Quarks
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Leptons
Higgs boson
W+
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Z0
g
W-
Forces
CERN
ACCELERATING SCIENCE