History of Particle Physics

- From atomic to particle physics:
  Nuclei, Nucleons, and Electrons
- The first carrier of a force: The Photon
- The first Mesons and Antimatter
- Neutrinos
- Strange Particles and the Eightfold way
- The November revolution and its afterglow
- The triumph of Symmetry:
  The Standard Model and Vector Bosons

From atomic to particle physics: <u>Discovery of the electron</u>

J.J.Thompson, 1897:

- Cathode rays deflected by fields
  - ⇨ negative electric charges (curvature under B-fields)
  - ⇨ No rays (waves), but particles!
- Cross electric and magnetic fields
  - ⇨ determine velocity (0.1 c) and
  - ⇨ charge-to-mass ratio (huge)

From atomic to particle physics: Discovery of the electron

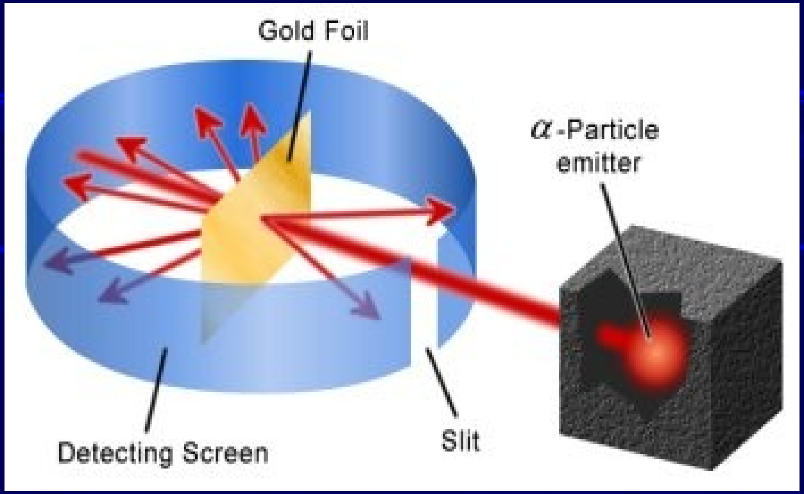
J.J.Thomson, 1897:

- Charge-to-mass ratio suggests: indirect evidence for negatively charged object with very small mass (no ion/atom with similar properties known)
  ⇨ "Corpuscles", their charge was dubbed "electron"
- Thomson's idea: part of the atom, but where?
  ⇨ Embedded in massive positive paste, compensating the electrons' charge ("plum pudding model")

From atomic to particle physics:
Nuclei and electrons

E.Rutherford's experiment 1911:

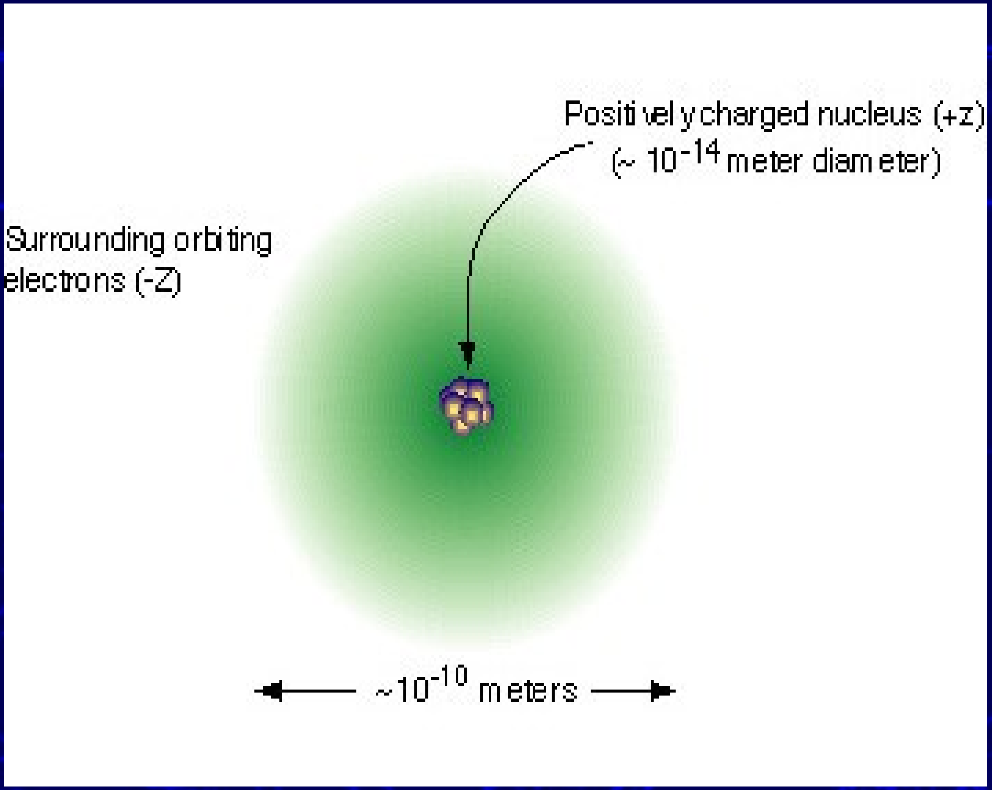
- Fire α-particles (ionized Helium atoms) onto a thin gold foil.
- Plum pudding model suggests moderate, diffuse deflection pattern.
- But: All scattering angles occur, majority of ions pass undisturbed through the gold foil, few scatter at potentially large angles.



From atomic to particle physics: **First hydrogen (atom) model**

Interpretation of Rutherford's experiment:

- Picture of atoms: Heavy, positively charged nuclei surrounded by negative, light electrons.
- The lightest nucleus (hydrogen) was called proton.

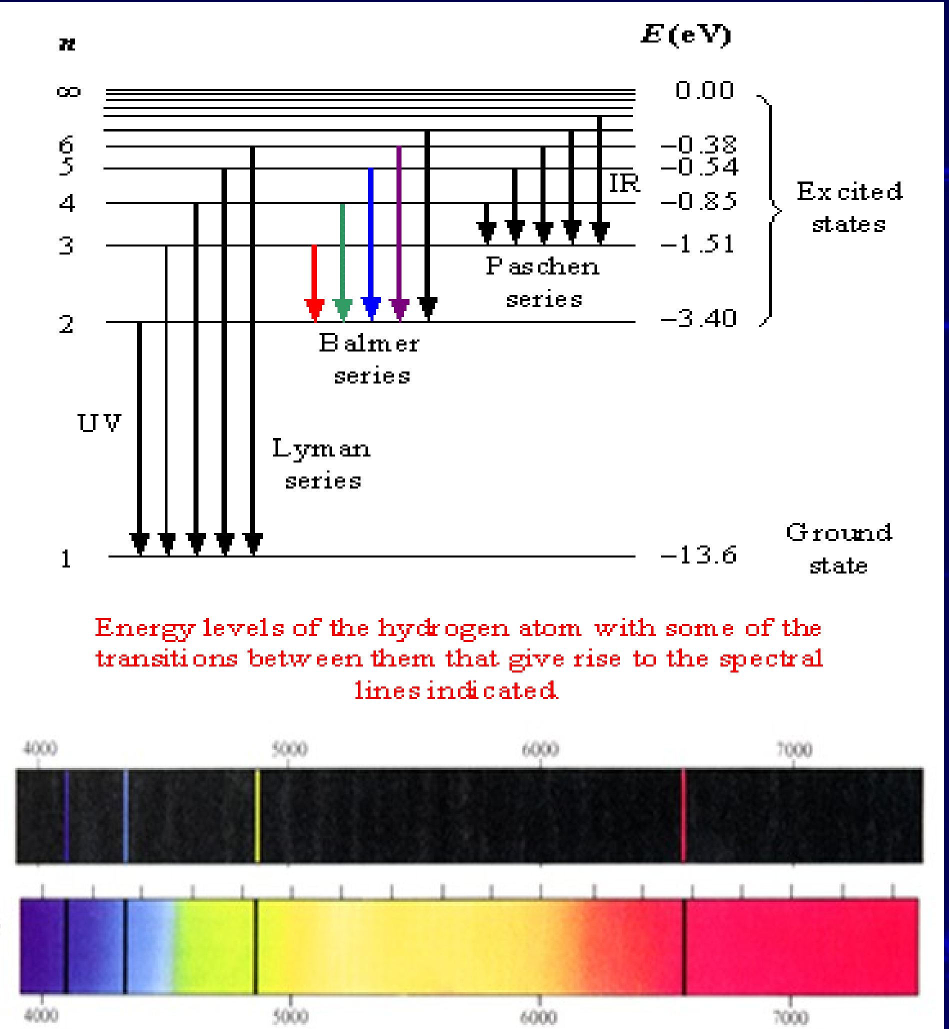


From atomic to particle physics:
First hydrogen (atom) model

(N. Bohr, 1914):

- A single electron circles the proton, a primitive version of quantum theory defines the absence of radiation and thus stable orbits.

➪ spectacular success: prediction of the hydrogen spectrum.



Energy levels of the hydrogen atom with some of the transitions between them that give rise to the spectral lines indicated.

The Hydrogen Spectrum
Above: Emission
Below: Absorption

From atomic to particle physics: The neutron

Aftermath of Rutherford's experiment:

- New problem: Next lightest atom (Helium) four times as heavy as hydrogen, but only two electrons. Similar for Lithium (three electrons, seven times as heavy), etc.. If positive and negative charges compensate, what makes them so heavy?

From atomic to particle physics: The neutron

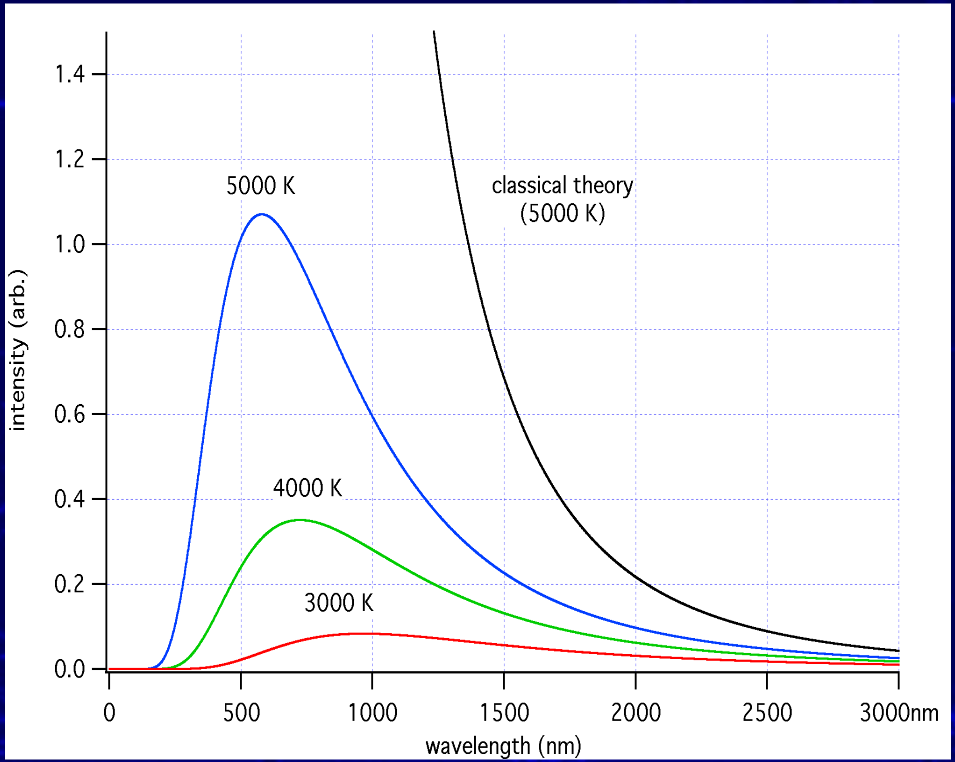
Discovery of the Neutron by J.Chadwick, 1932:

- Bombard Beryllium with α-particles
  ⇨ very penetrating non-ionising radiation is emitted
- Radiation through paraffin ⇨ protons are emitted.
- Measure speed of protons
  ⇨ original radiation cannot be γ's ⇨ new particle
- Nearly the same mass as the proton but no charge.
  ⇨ Heisenberg, 1932: Both neutron and proton are
  two manifestation of the same state, the Nucleon.

The first carrier of a force:
The photon

Black body radiation

- Problem in 1900: The electromagnetic spectrum emitted by a hot black body. Statistical physics failed completely in explanation, predicting the total energy emitted to be infinite.



- Side-remark: "Perfect" black-body radiation is observed in cosmic microwave background.

The first carrier of a force:
The photon

M.Planck 1900:

- proposal: electromagnetic radiation comes quantised, relation of energy E and frequency ν is

$$E = h\nu$$

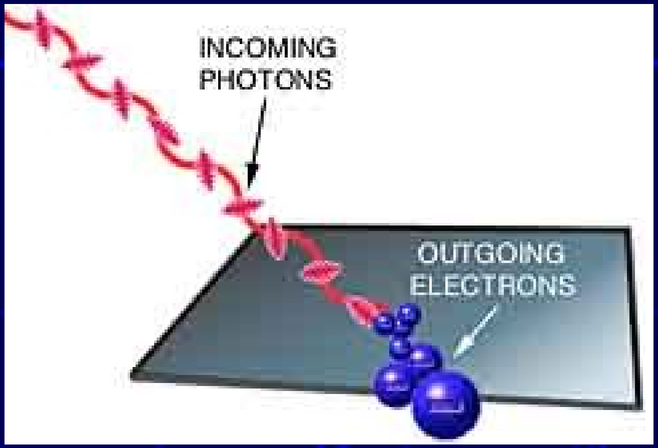
with constant h (Planck's constant)

Note: Planck gave no reason for quantization.

The first carrier of a force:
The photon

Einstein's explanation of the photoelectric effect (1905):

- Quantization is a natural, intrinsic property of electromagnetic radiation.
  ➪ Explains of photoelectric effect: Electromagnetic radiation "kicks" electrons out of metal. Process depends on frequency of light only, not on intensity.



- Energy of electrons: $E_e = h\nu - W_{\mathrm{out}}$
  (W_{out} is a material-specific energy needed for the electrons to leave the metal)

The first carrier of a force:
The photon

Discovery of the Compton effect (A.H.Compton, 1923):

- Light scattered off a particle with mass m at rest changes wavelength:

$$\lambda \to \lambda' = \lambda + \frac{h}{mc}(1 - \cos\theta)$$

- Exactly the behaviour of a massless particle in relativistic physics (energy-momentum conservation).
- Quanta of electromagnetic radiation are photons, symbolised by γ. First example of:

Interactions are mediated by exchange particles.

Cosmic evidence: Mesons and Antimatter

Proposing mesons

Yukawa 1934

- First prediction of mesons:
  Answer to the question why neutrons and protons bind together in nucleus.
  Underlying assumption: A new force, short-ranged mediated by massive mesons.
- Estimate: 3-400 times the electron mass.
  From uncertainty principle $\Delta E \Delta t \geq \hbar$
  with time given by nucleon radius as $\Delta t \approx r_0 / c$
  ⇨ $\Delta E \approx mc^2 \approx \hbar c / r_0 \approx 0.2\mathrm{GeV} \cdot \mathrm{fm}/1\mathrm{fm} = 0.2\mathrm{GeV}$

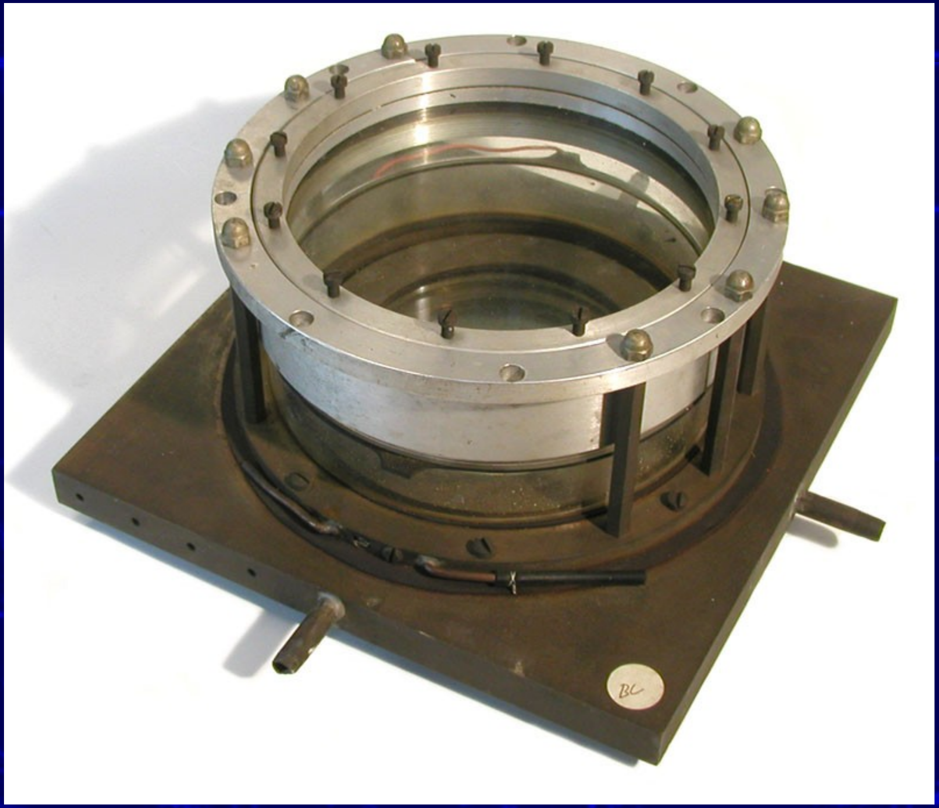
Cosmic evidence: Mesons and Antimatter

Finding the first mesons

Anderson & Neddermeyer,
Street & Stevenson (1937):

- Finding such particles in cosmic rays using cloud chambers.

But: wrong lifetime (too long, indicating weaker interaction), inconsistent mass measurements

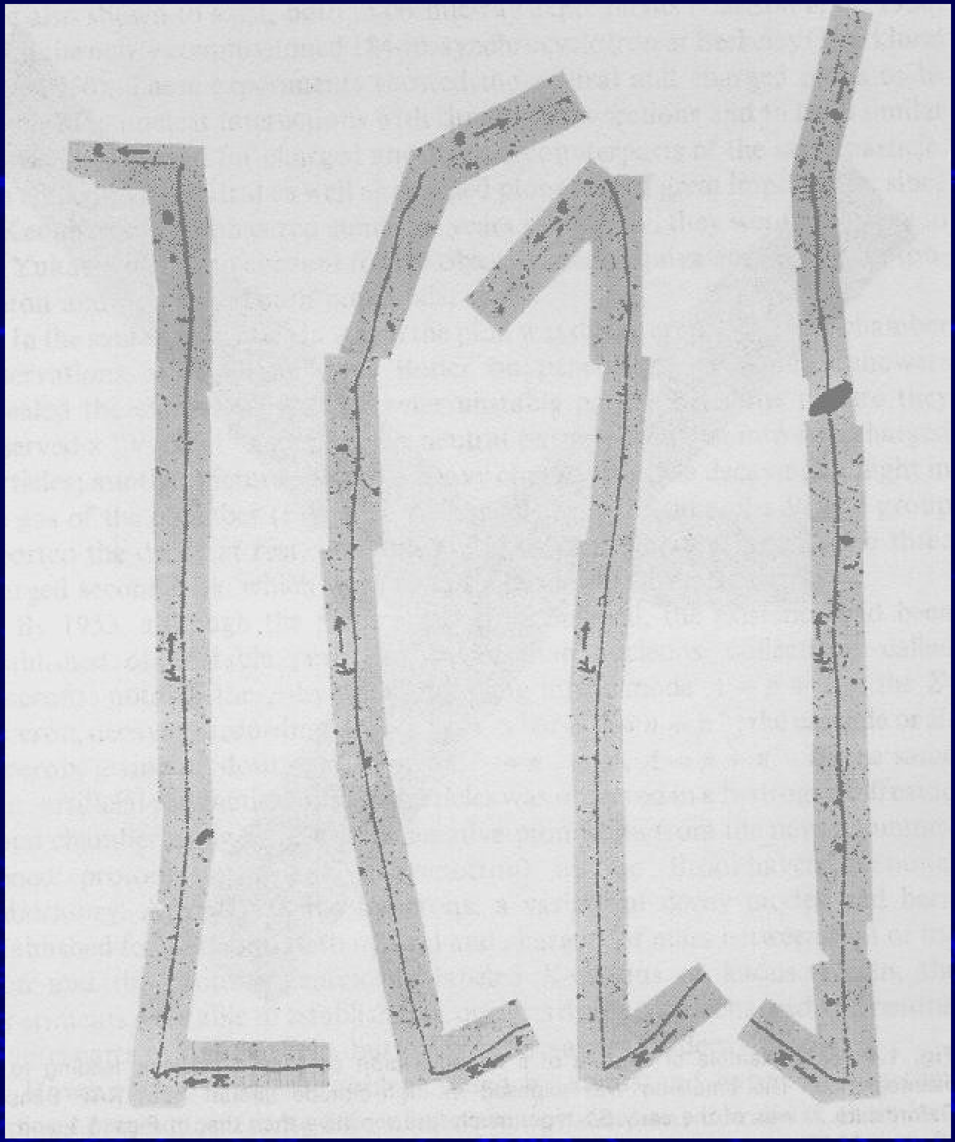


Cosmic evidence: Mesons and Antimatter

True mesons and the muon

Two decisive experiments to clarify the situation (Rome, 1946 & Powell et al. in Bristol, 1947):

- Technique: photo emulsion
- Two new particles: One weakly interacting, the muon, μ, one strongly interacting, the pion, π



Cosmic evidence: Mesons and Antimatter
True mesons and the muon

Properties of the two new particles

- The muon, μ has longer lifetime ➪ weak interactions ➪ in fact a lepton (like electron, 200 times heavier)
- the pion, π decays quickly ➪ strong interactions (Found by Powell on mountain tops.) ➪ this is the true meson postulated by Yukawa.

(Same conclusion was reached on theoretical grounds by H.Bethe and R.E.Marshak.)

Cosmic evidence: Mesons and Antimatter

Proposing antimatter

P.A.M. Dirac, 1927:

- Non-relativistic QM was quickly completed (1923-26), but relativistic version much harder. Main problem: Relativistic equation $E^2 = p^2 + m^2$ yields solutions for negative energies ⇨ all particle states decay into increasingly negative states ⇨ no stable ground state.
- Proposal: Fill "sea" of negative energy states, (Fermi-character prevents double fillings).

Cosmic evidence: Mesons and Antimatter

Proposing antimatter (cont'd)

P.A.M. Dirac, 1927:

- Interpretation of "holes" in the sea: absence of negative energy looks like net positive energy.
- The related particle must have same mass as ordinary particles, but opposite charge ⇨ antimatter

Stueckelberg-Feynman antimatter-interpretation (1947):

- Negative energy solutions are indeed positive energy solutions of a new particle ⇨ treating electrons and positrons on equal footing ⇨ no more holes.

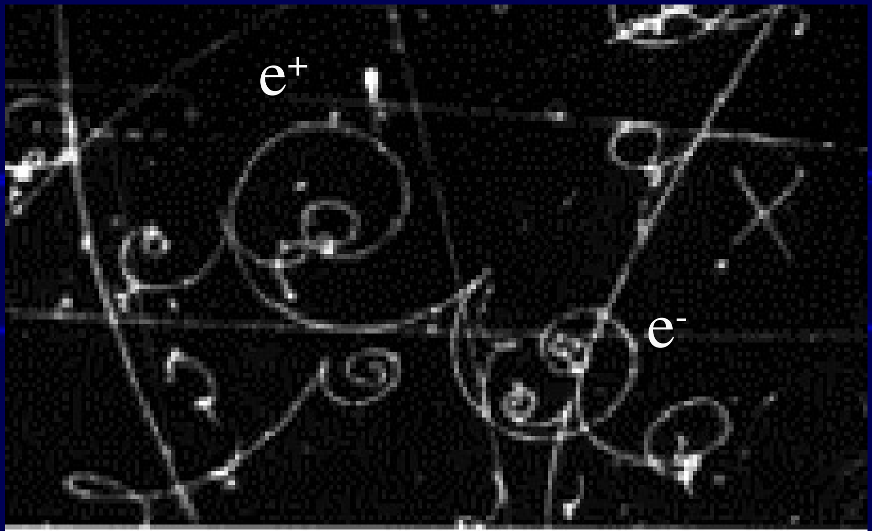
Cosmic evidence: Mesons and Antimatter

Finding antimatter

Anderson, 1931:

- Finding a particle electron's mass but opposite charge ⇨ electron's antiparticle, "positron."

"On August 2 1932 during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field 15,000 gauss) designed in the summer of 1930 by Prof R A Millikan and the writer the track shown in fig 1was obtained which seemed to be interpretable only on the basis of a particle carrying a positive charge but having the same mass of the same order of magnitude as that normally possessed by a free electron."



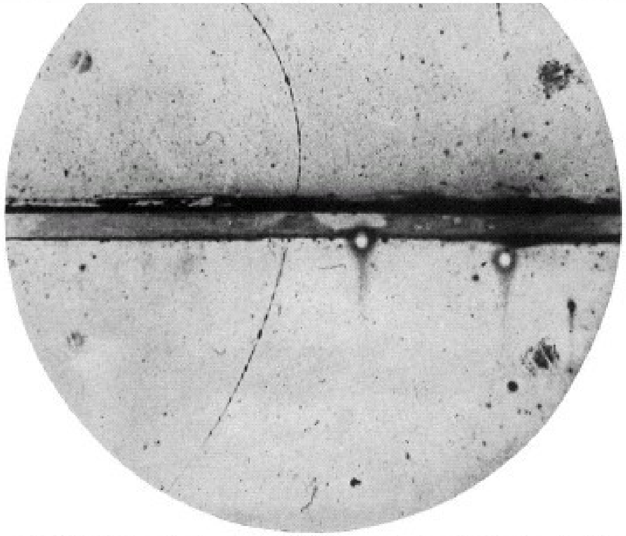


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Cosmic evidence: Mesons and Antimatter

Finding antimatter

The 50's: More antiparticles

- Anti-proton found 1955 at Bevatron accelerator (running at 6.5 GeV in Berkeley)

the anti-neutron was found there in 1956.

Cosmic evidence: Mesons and Antimatter

Crossing symmetry

- There is a symmetry called "crossing symmetry": Suppose a reaction $A + B \to C + D$ is known to occur. Then, any of the particles A, B, C, D can be "crossed" over as antiparticle to the other side

$$A \to \bar{B} + C + D$$

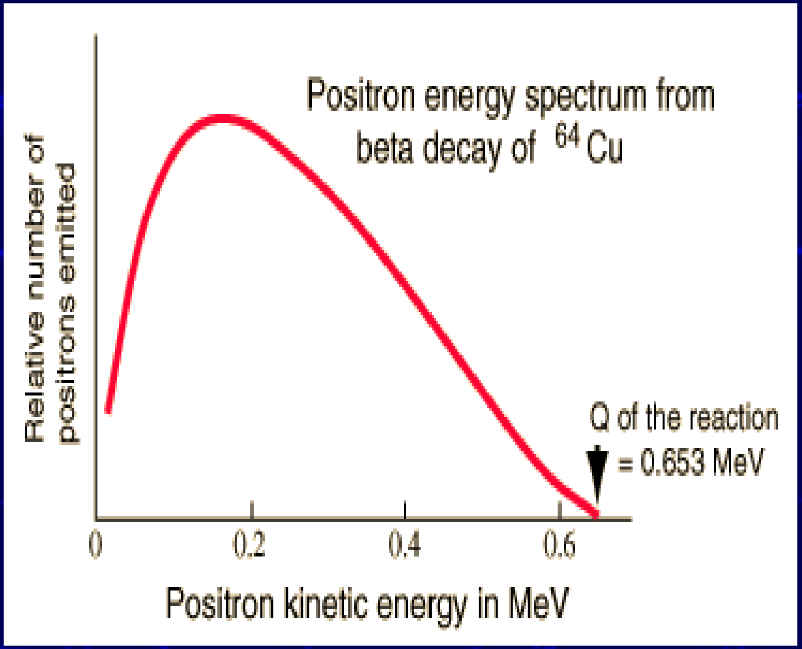
$$A + \bar{D} \to \bar{B} + C$$

- In addition, the reverse action $\bar{C} + \bar{D} \to \bar{A} + \bar{B}$ occurs, due to the principle of detailed balance.
- Note: Although in principle possible under crossing, processes may not be allowed "kinematically", due to energy thresholds.

The elusive neutrinos

Radioactive β-decays: $A \rightarrow Be^-$

- Problem: Energy fixed in two-body decays due to energy-momentum conservation
- But: Found continuous spectrum of electron energies.



Pauli (1930):

- Proposal of a new particle, electrically neutral (to conserve charge and remain invisible)

Pauli's letter to the "dear radioactive ladies and gentleman"

Abschrift/15.12.56 PW

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

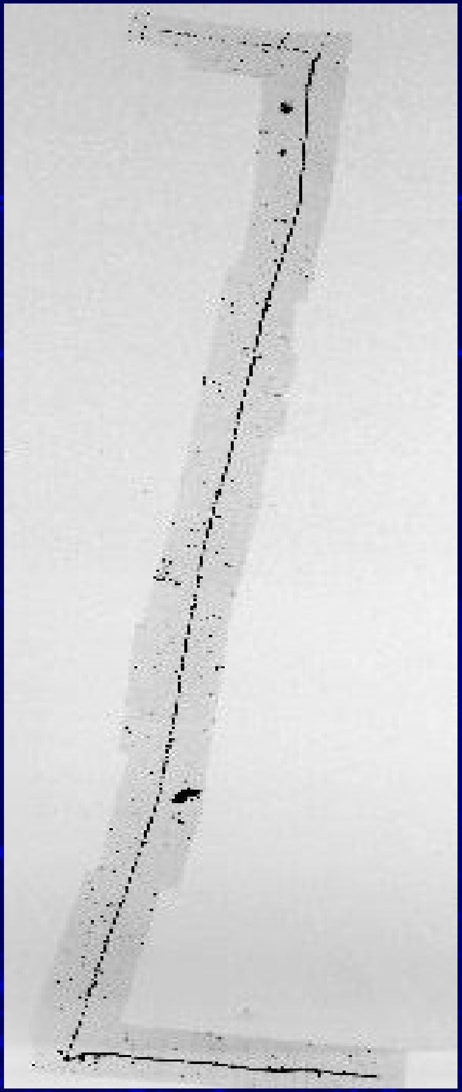
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

The elusive neutrinos

(but are they really there?)

- Neutrinos not only in radioactive β-decays $p \to n e^{+} \nu$ and $n \to p e^{-} \nu$, but also in the decay of the pions and muons.
- Check left emulsion-photo (again, from Powell): A pion enters from left and decays into a muon and neutrino, the former travels upwards and decays again, into an electron and neutrinos: $\pi \to \mu\nu$, $\mu \to e\nu\nu$



The elusive neutrinos

(they are really there!)

- Neutrinos only very weakly interacting
  (could fly through lightyears of lead without interaction)
- Therefore: intensive sources, large targets needed.
- Cowan & Reines at the Savannah River nuclear reactor (1956) prove reaction $\bar{\nu} p^+ \rightarrow n e^+$
- Davis & Harmes (1959) prove existence of anti-neutrinos through absence of $\bar{\nu} n \rightarrow p^+ e^-$
- Konopinski & Mahmoud (1953) propose a conserved lepton number L. L=+1 for electrons muons and neutrinos, L=-1 for positrons, antimuons, anti-neutrinos.

The elusive neutrinos

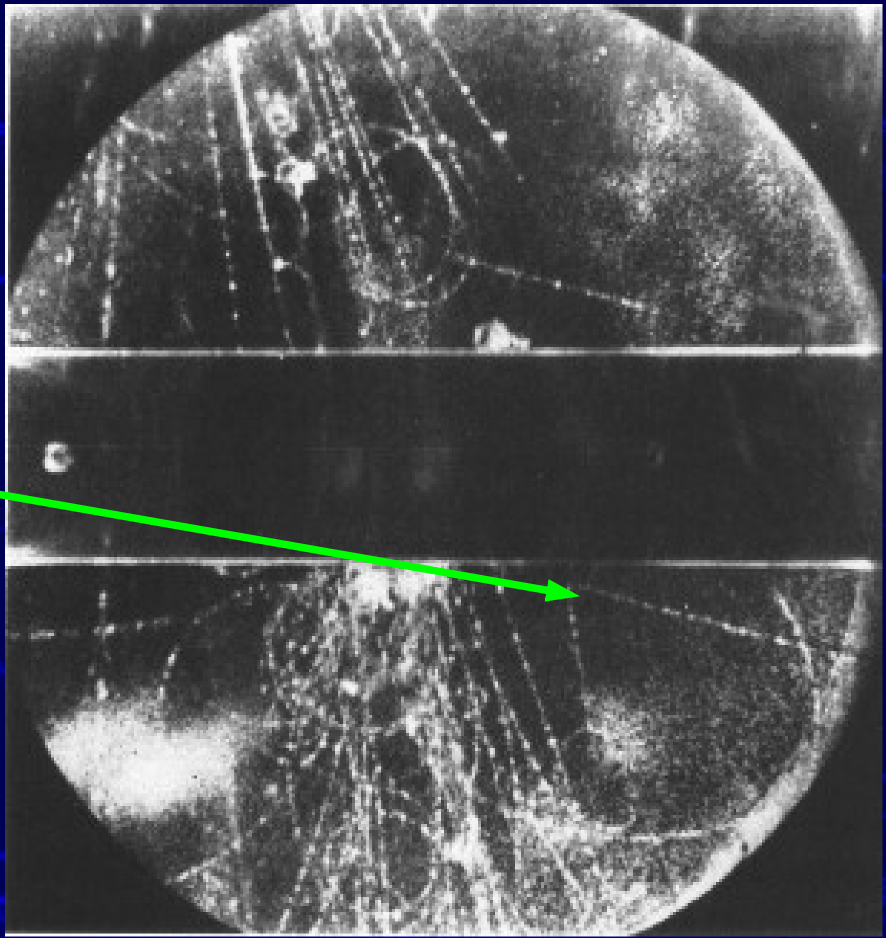
(they are really there!)

- Further twist: No reaction $\mu^- \to e^- \gamma$ ever observed
  ⇨ lepton number L is "per kind"
  ⇨ muon decay in fact looks like $\mu^- \to e^- \bar{\nu}_e \nu_\mu$
- Test of the two-neutrino hypothesis by Lederman, Schwartz, Steinberger et al. at Brookhaven 1962. Using 10^{14} antineutrinos from π^- decays, they found 29 times the reaction $\bar{\nu} + p^+ \to \mu^+ + n$ but no reaction of the kind $\bar{\nu} + p^+ \to n + e^+$. For only one kind of neutrino both reactions should come in equal numbers.

Strangeness and the quark model
Finding strange particles

Rochester & Butler (1947):

- Cloud chamber experiment with cosmic rays. Unusual "fork" of a π^+ and a π^-.
- Interpretation: Cosmic ray particles with mass between π and p, the kaon, K.
- Like pions, but strangely long lifetime (decay to pions or a muon and neutrino)

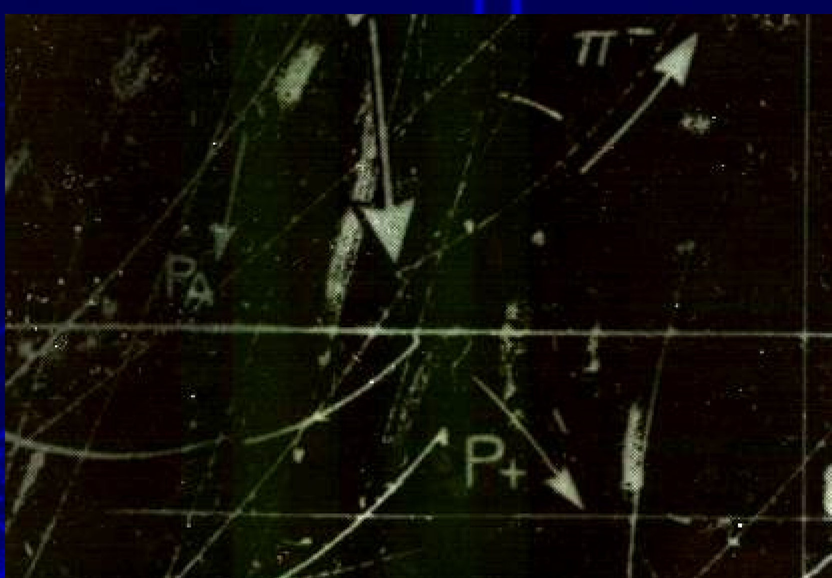


Strangeness and the quark model

Finding strange particles

Anderson (1950):

- Another "strange" particle, decaying into proton and π^+, $\Lambda \rightarrow p^+\pi^-$.



Why are they "strange":

- With the advent of the Bevatron it became clear: Strange particles (kaons and lambdas) are copiously produced, but decay slowly (strong interaction in production, weak interaction in decay)!

Strangeness and the quark model

Finding strange particles

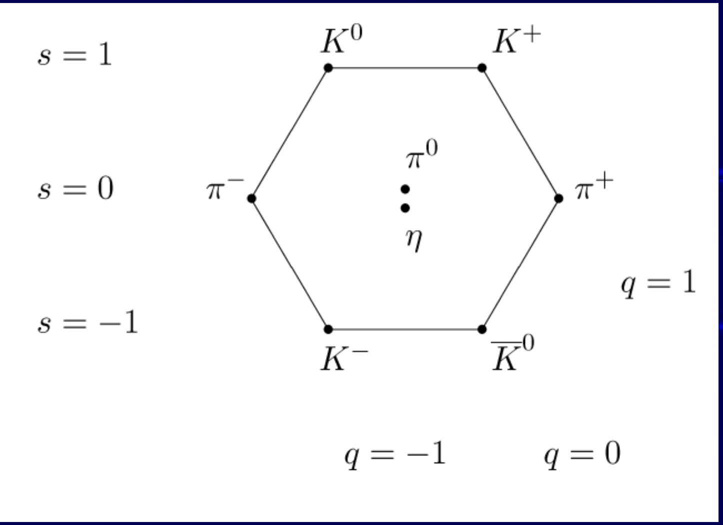
More on strange particles:

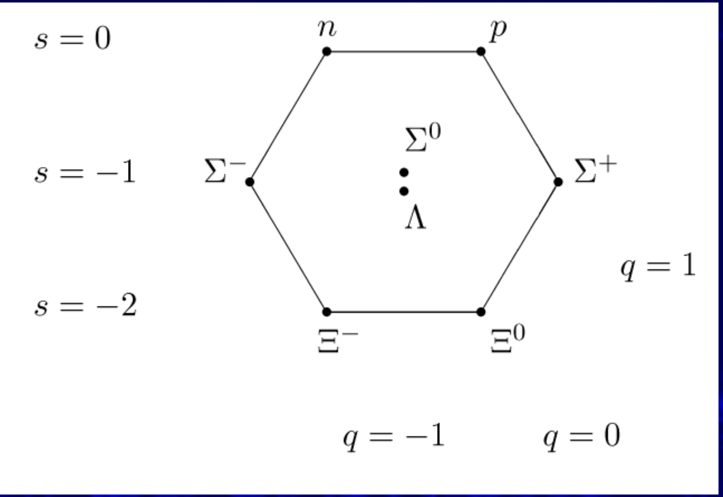
- Only produced in pairs ⇨ Gell-Mann and Nishijima propose a new quantum number (1953): strangeness.
- Strong interactions conserve strangeness, weak interactions don't.
  ⇨ Allowed: $p^+ + \pi^- \rightarrow K^+ + \Sigma^-, K^0 + \Lambda \ldots .$
  ⇨ Forbidden: $p^+ + \pi^- \rightarrow \pi^+ + \Sigma^- \ldots .$
- Side remark: Baryon number (B) is also conserved

Strangeness and the quark model
The eightfold way

Gell-Mann (1961):

- In the 50's many new particles found, but at first no pattern.
- Gell-Mann found geometrical patterns (hexagons) for particles with identical spin (0 and 1/2). Strangeness is along horizontal lines, charge along diagonals. Note that there are two neutral states in the middle of each hexagon.



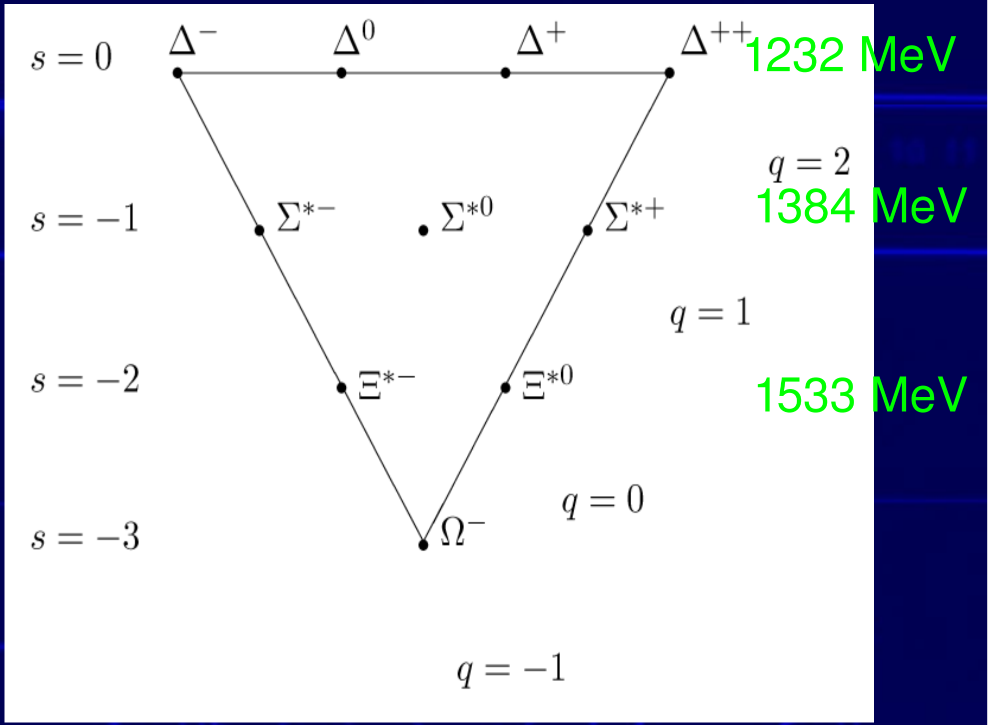


Strangeness and the quark model

The eightfold way

Gell-Mann (1961):

- Eightfold way named after the eight states (octet) organised in the hexagons.
- But not only hexagons, also larger triangles (spin 3/2), ten states ⇨ decuplet.
- In 1961, tip not found. Gell-Mann's prediction: m = 1672 MeV, plus production and (long) lifetime.



Strangeness and the quark model

The eightfold way

Finding the Ω^- (1964) – triumph of the eightfold way

Chain of events in the picture:

$K^- + p \rightarrow \Omega^- + K^+ + K^\circ$

(strangeness conserving)

$\Omega^- \rightarrow \Xi^\circ + \pi^-$

($\Delta S = 1$ weak decay)

$\Xi^\circ \rightarrow \pi^\circ + \Lambda$

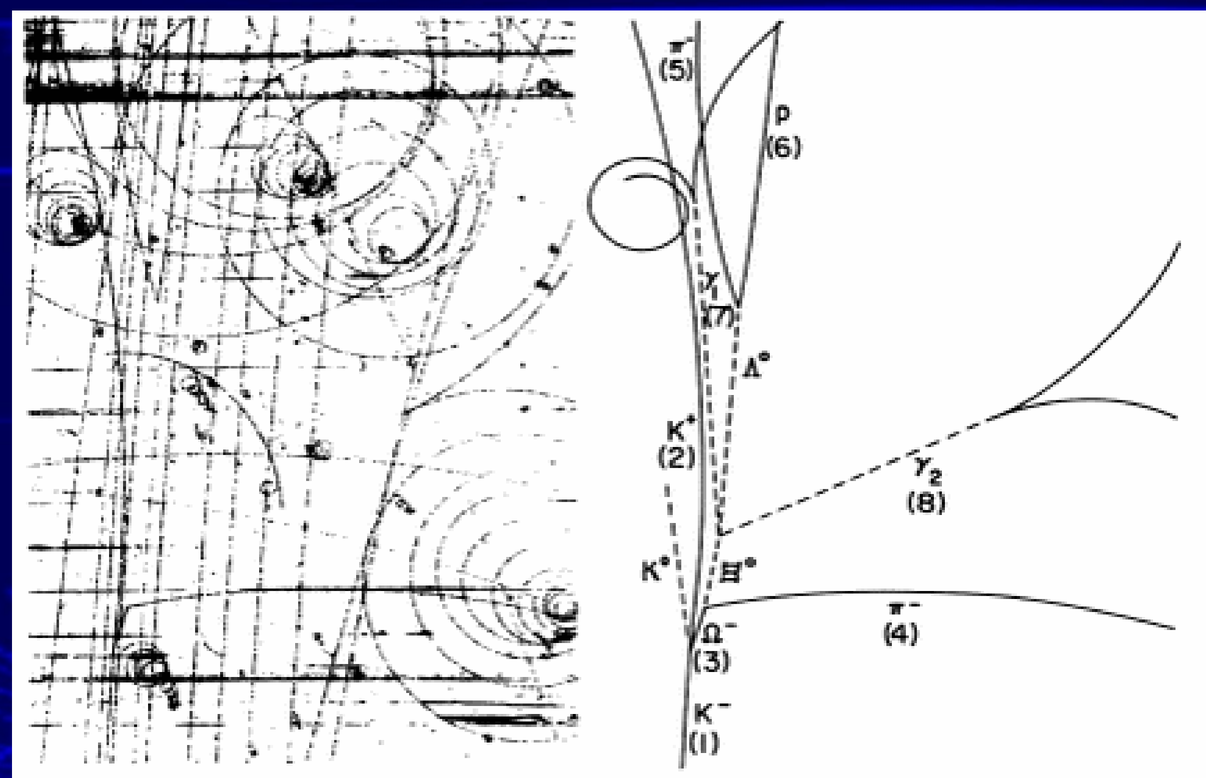
($\Delta S = 1$ weak decay)

$\Lambda \rightarrow \pi^- + p$

($\Delta S = 1$ weak decay)

$\pi^\circ \rightarrow \gamma + \gamma$

(electromagnetic decay)

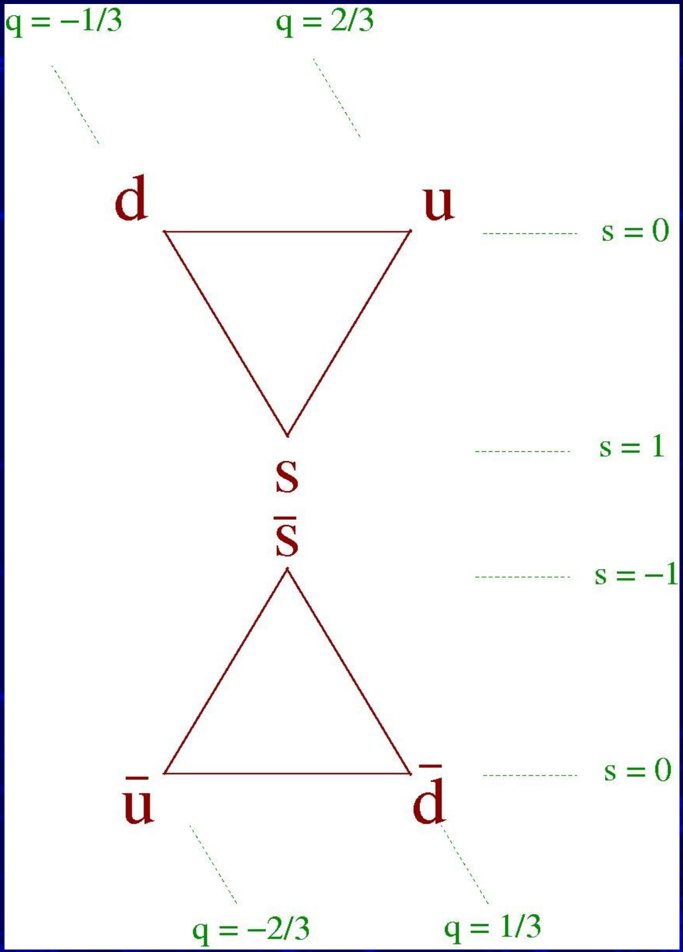


Strangeness and the quark model
The quark model

Gell-Mann & Zweig (independent from each other 1964):

- Eightfold way extremely successful, but why?
- Suggestion: Hypothetical particles ⇨ quarks + their antiparticles

  (from a poem by Joyce: "… three quarks for master mark…")
- originally thought as mnemonic device to keep track of group theory labels ⇨ became real!

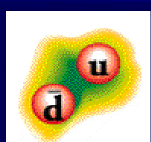


Strangeness and the quark model

The quark model

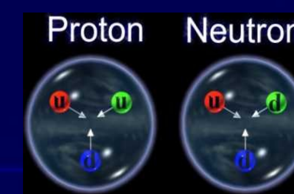
Gell-Mann & Zweig (independent from each other 1964):

- quarks (spin 1/2 fermions) form mesons and baryons:
  Meson = quark + anti-quark, baryon = three quarks



$$\pi^+ = u\bar{d},\ \pi^- = d\bar{u},\ \pi^0 = \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right),$$

$$p = uud,\ n = udd,\ \Sigma^0 = uds,\ \Delta^{++} = uuu, \ldots$$

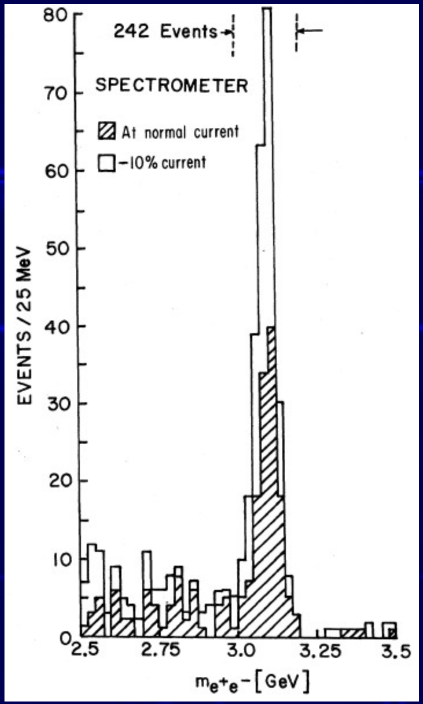


- Problem: Fermi-statistics for decuplet baryons (Δ^{++})
  ⇨ solution: new quantum number (colour: rgb)
- But: All observable particles are colourless
  (red-antired, red-blue-green, etc.).

More generations

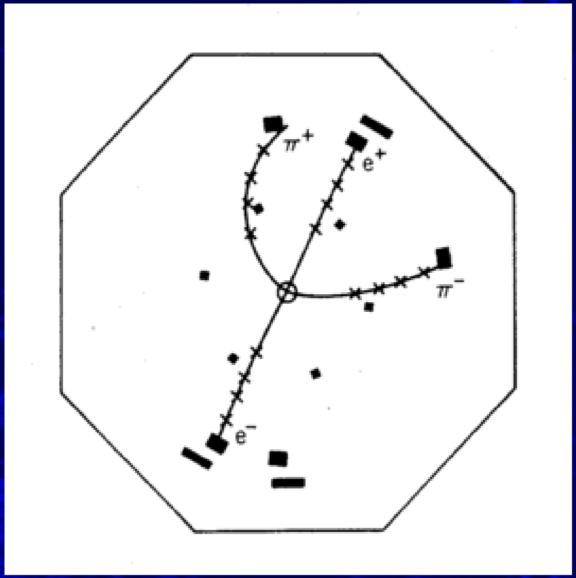
The November revolution

Discovery of the J/Psi (November, 1974):



- S.C.C.Ting et al. at Brookhaven AGS proton synchrotron,

$$pBe \rightarrow J(\rightarrow e^+e^-) + X, \; m = 3.1\text{GeV}$$



- B.Richter et al. at SLAC/Spear ee-collider with Mark-I detector

$$e^+e^- \rightarrow \Psi \rightarrow e^+e^-, \; m = 3.105\text{GeV}$$

More generations
Charm

Discovery of the J/Psi (November, 1974)

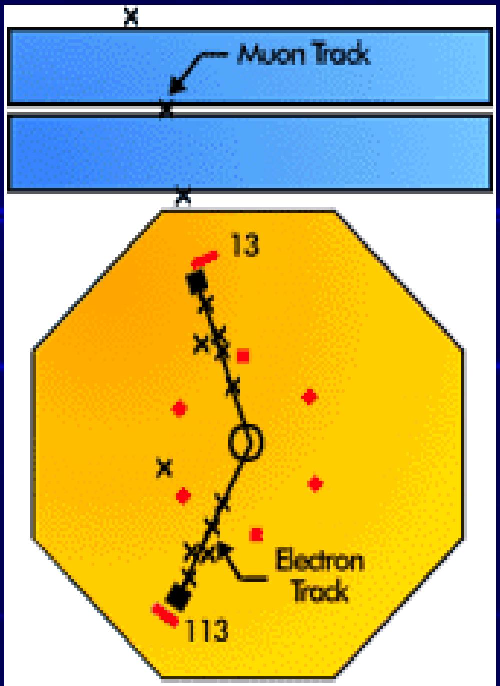
- J/ψ found as a narrow resonance, decaying into leptons (electromagnetically!) with significant probability
  ⇨ interpretation as a bound state of two new quarks (charm)
- Mass: larger than the proton mass !!! ($m_c \approx 1.5\mathrm{GeV}$)

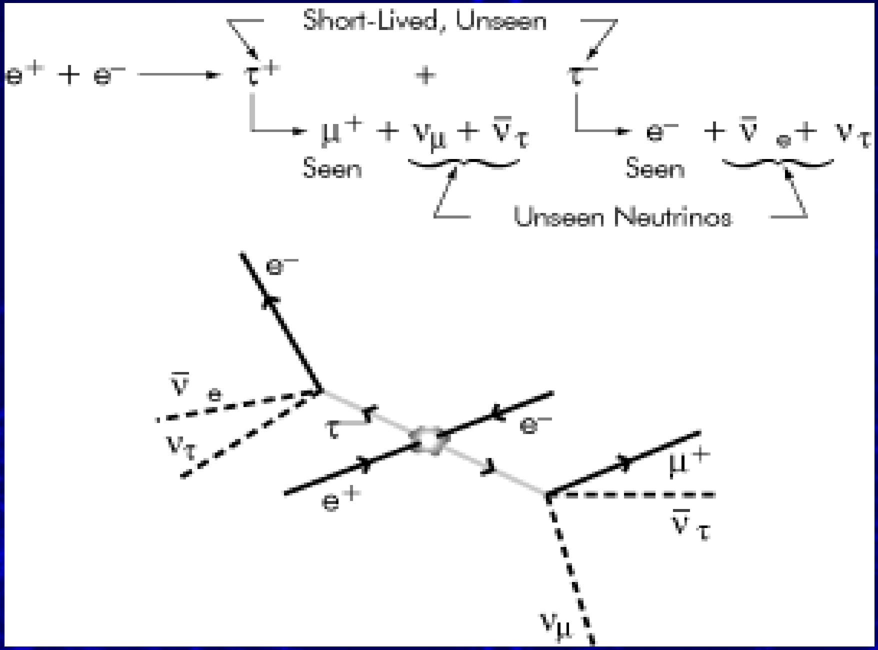
More generations

The discovery of the tau

Discovery of the tau (M.Perl, 1975):

- Found at SLAC/Spear at 4 GeV
- Reaction: $e^+e^- \rightarrow \tau^+\tau^-,\ m_\tau \approx 1.8\mathrm{GeV}$
- Interpretation: A new lepton!





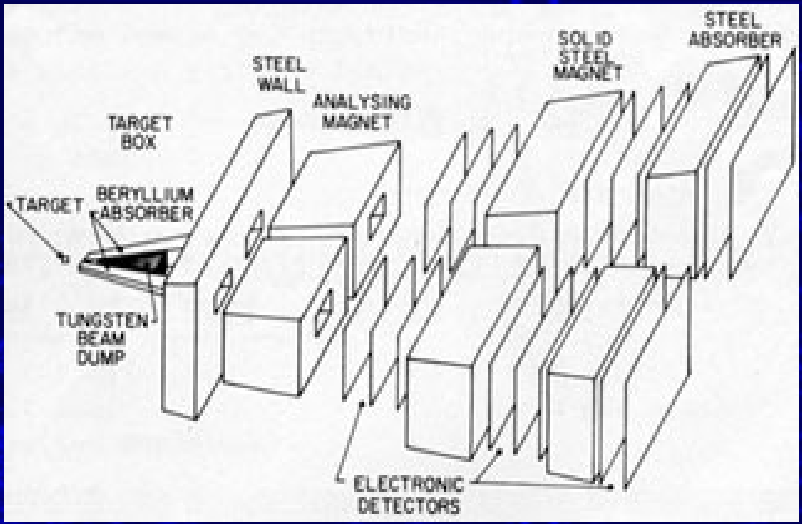
- Interesting signature, due to $\tau^\pm \rightarrow \ell^\pm + \mathrm{invisible}$
- 24 events out of 35000 yield $e^+e^- \rightarrow \mu^+e^- + \mathrm{inv.}$

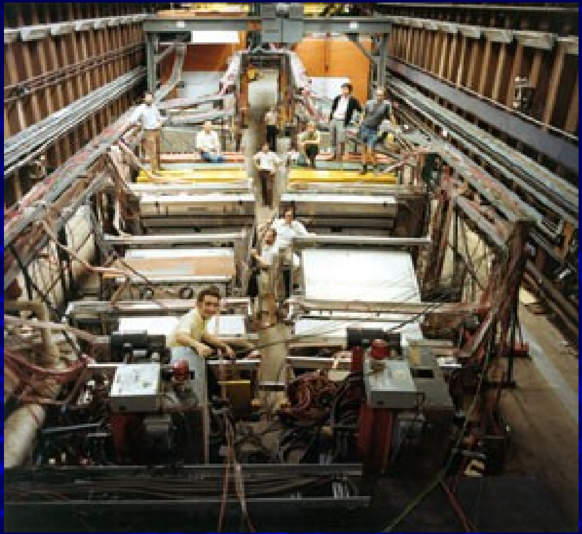
More generations

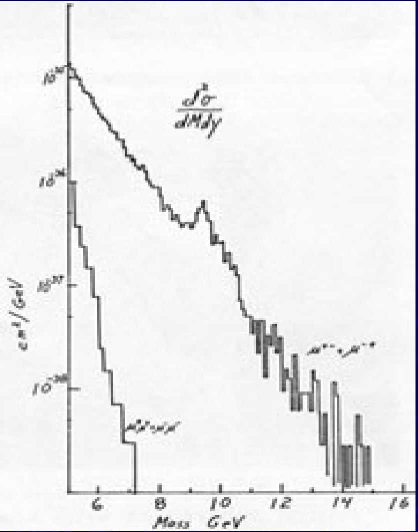
The discovery of beauty/bottom

L. Ledermann (1977) at Fermilab

- Observation of a Dimuon Resonance at 9.5 GeV in 400 GeV Proton-Nucleus Collisions: $\Upsilon(1s) \rightarrow \mu^+\mu^-$
- Interpretation (again) bound state of a new quark (beauty or bottom, $m_b \approx 4.8\mathrm{GeV}$)





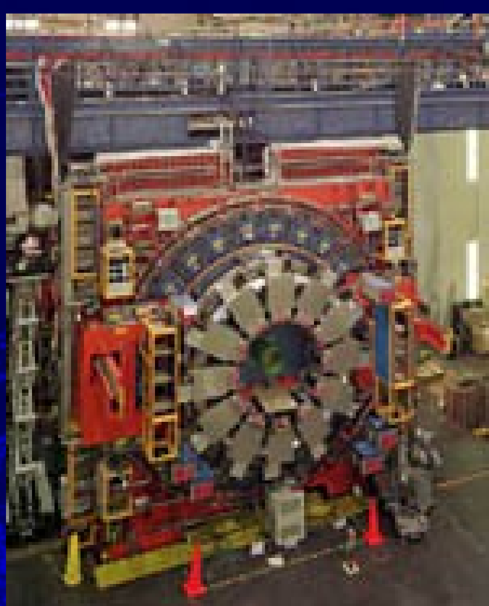


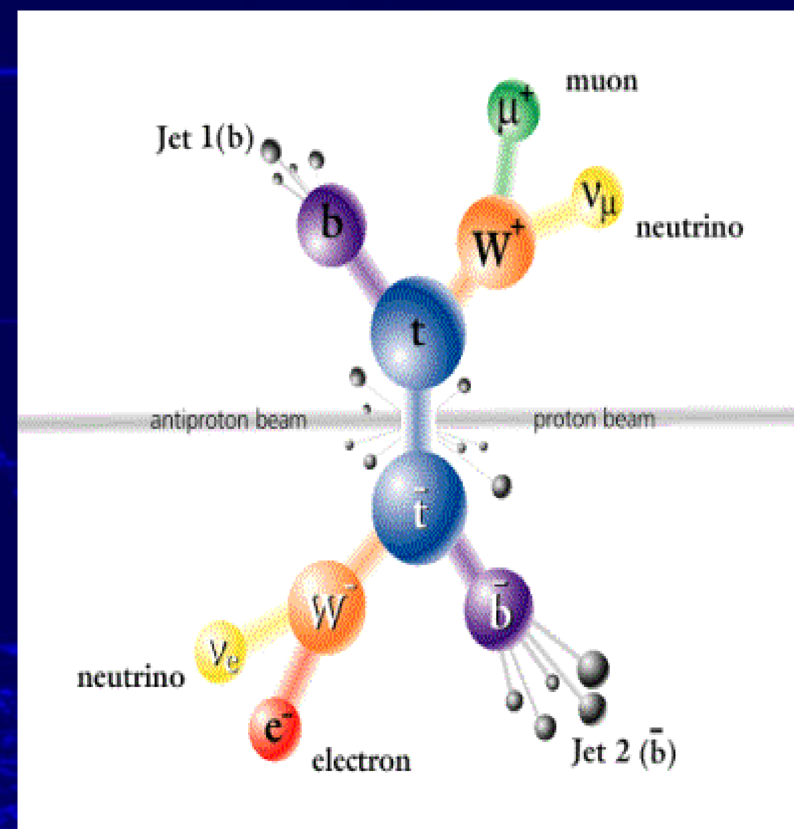
More generations

The discovery of truth/top

CDF and D0 (1995) at Fermilab

- CDF: 37 events over estimated 12, D0: 17 over 4.
- $m_t = 176 \pm 8 \pm 10\text{GeV (CDF)}$,
  $m_t = 199 \pm 20 \pm 22\text{GeV (D0)}$





More generations

The fundamental building blocks

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

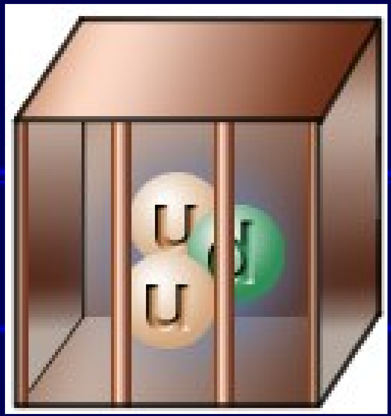
Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

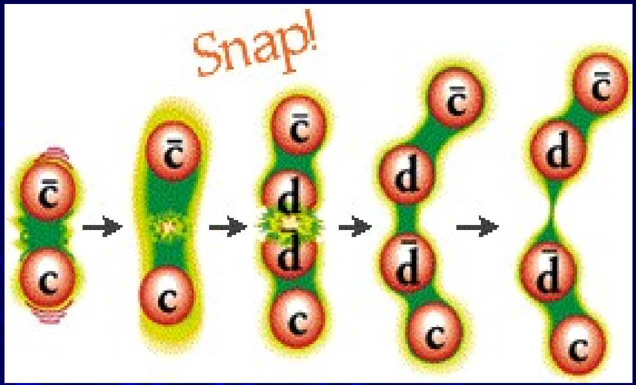
Vector bosons

The discovery of the gluon

- Remember: Quark "confinement" disallows the presence of free quarks. Only "white" hadrons are allowed. This is a property of the strong interactions.



- But what happens when a uark-antiquark pair is stretched?
- Answer: The colour force field is stretched, until it "snaps", producing new quarks.



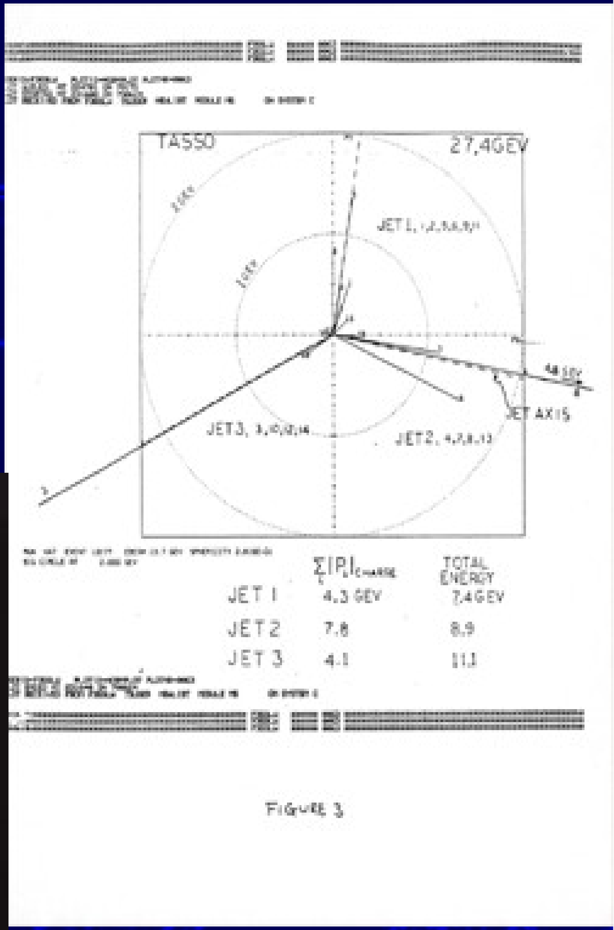
- Question: Is there a dynamical explanantion?

Vector bosons

The discovery of the gluon

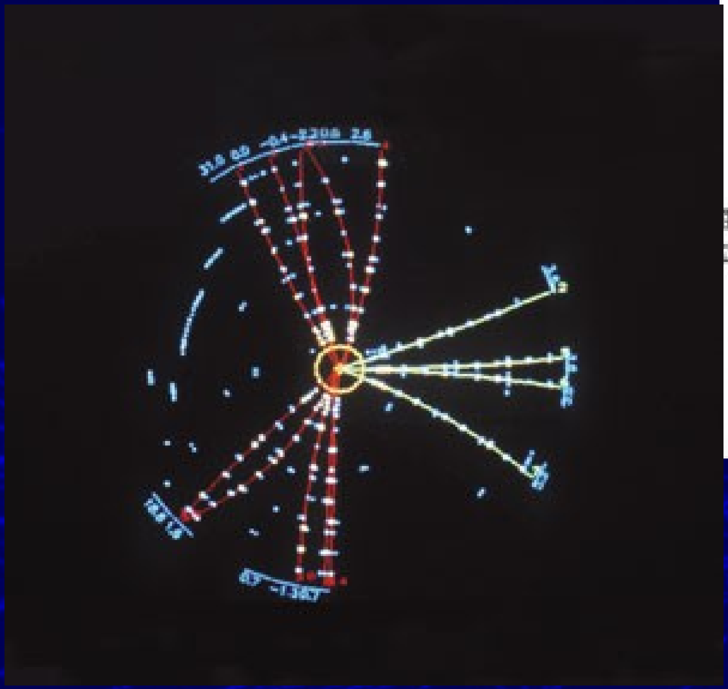
TASSO (1979) @ DESY (Petra collider)

- Is there a boson (like the photon in electromagnetic interactions) involved in the strong interactions?



- Yes !
  The gluon …

- … manifests itself 1979 in "three-jet" events



Vector bosons

Weak interactions

- Remember: Weak interactions extremely short-ranged, mediating β-decays and the decays of muons, taus, kaons, etc..
- First theory of weak interactions as "contact" interactions of four fermions. due to E.Fermi (1933): Organised as interaction of two currents, leads to distinction charged current/neutral current according to charge associated with the interaction between the currents.

Vector bosons

Weak gauge bosons

S.Glashow, S.Weinberg & A.Salam (1968)

- Formulation of a theory of weak interactions as a gauge theory (like QED for electromagnetic interactions). Demand weak gauge bosons (W and Z).

G.'t Hooft & T.Veltman (1972)

- Proof that this theory is theoretically consistent.

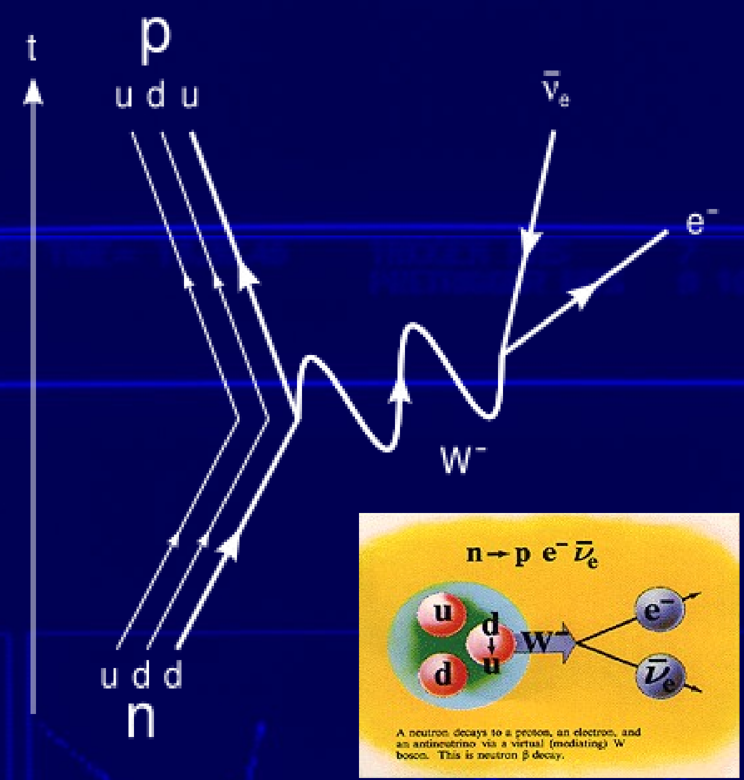
P.Higgs; R.Brout & F.Englert; G.Guralnik, C.R.Hagen & T.Kibble (1960's)

- Spontaneous symmetry breaking to give masses to the gauge bosons and the fermions.

Vector bosons

Weak gauge bosons

- When a quark or lepton changes type (a muon changing to an electron, for instance) it is said to change **flavour**.
- All flavour changes are due to the weak interaction.



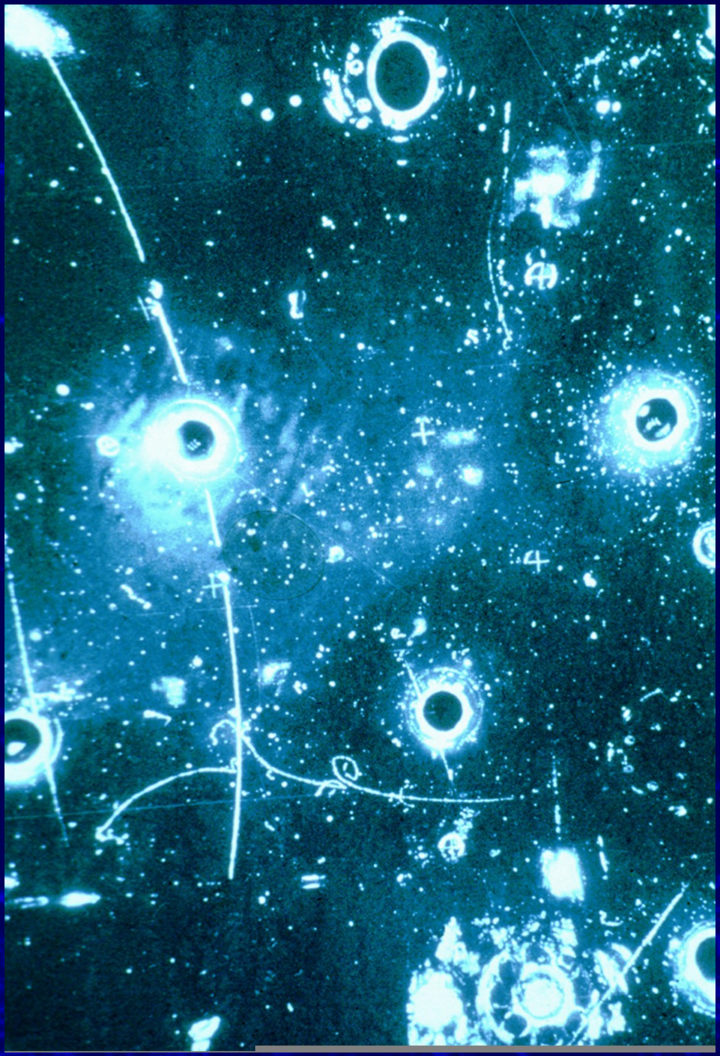
- The force carrier particles of the weak interactions are the **W+**, **W-**, and the **Z** particles. The W's are electrically charged and the Z is neutral, all are massive, in contrast to the photon and gluon.

Vector bosons

Evidence for neutral currents

Gargamelle at CERN (1973):

- Neutrinos interact with matter in a 1200 litre bubble chamber.
- Here: A neutrino interacts an electron (the horizontal line) and evades unseen.
- This is the first "photo" of a neutral current interaction.

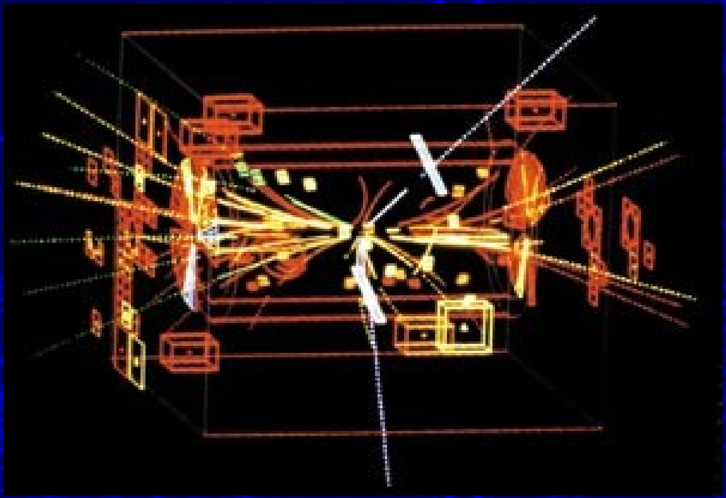


Vector bosons

Discovery of the weak bosons

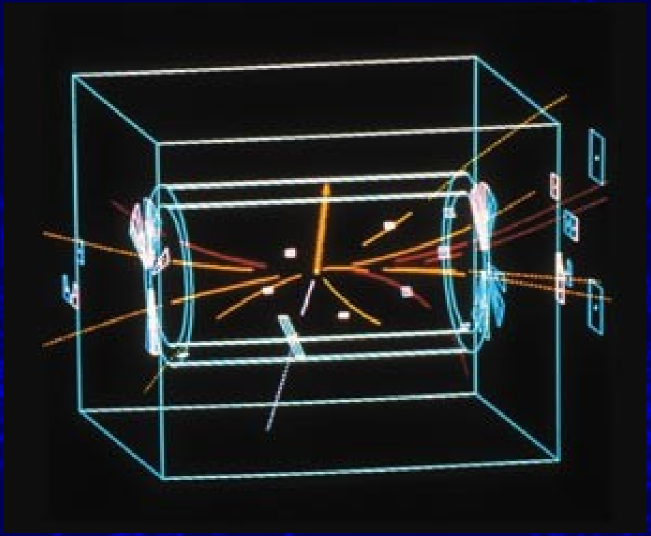
UA1 and UA2 at CERN (1983):

- proton-antiproton collisions in two interaction regions at $E = 540$ GeV.
- 54 $W \to e\nu$ events and 4 $Z \to ee$ events at UA1. First mass measurements: $m_W \approx 80.3\mathrm{GeV}, m_Z \approx 95.5\mathrm{GeV}.$



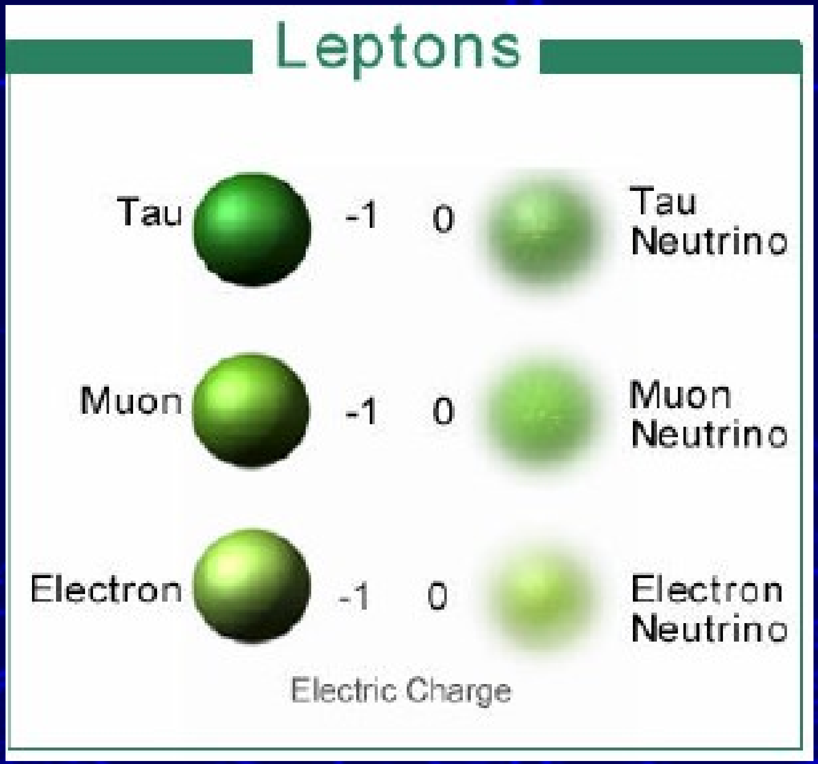
$\underleftarrow{Z \to ee}$

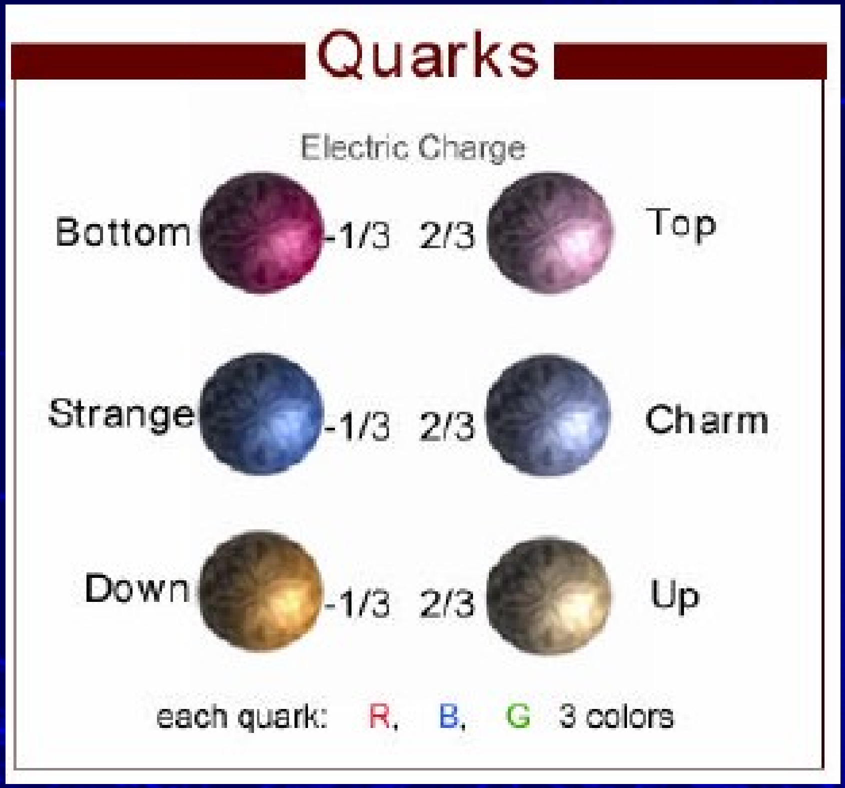
$\underrightarrow{W \to e\nu}$



The Standard Model

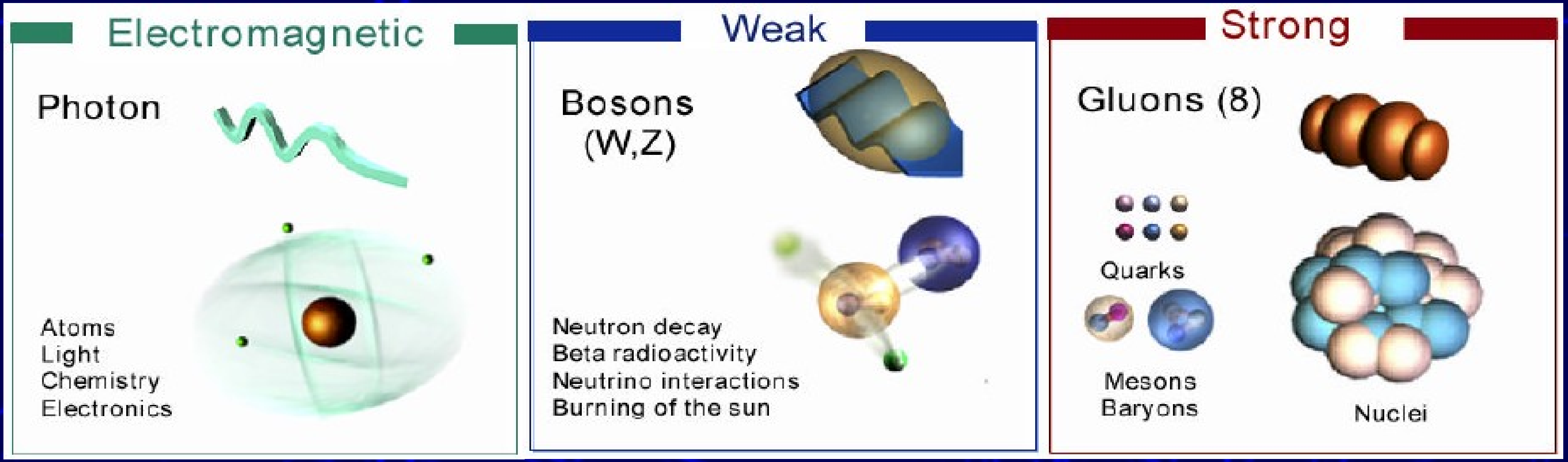
- The matter sector: spin-1/2 fermions in three generations (families), coming as leptons and quarks





The Standard Model

- The gauge/interaction sector: spin-1 bosons mediate electromagnetic, weak and strong interactions. Masses as a consequence of spontaneous symmetry breaking



- Manifestation of this: Higgs boson, yet not found.
- That's why LHC has been built … .