II. Leptons, quarks and hadrons

à *Leptons* are spin-1/2 fermions, not subject to strong interaction

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

$$M_e < M_\mu < M_\tau$$

v Electron e^-, muon μ^- and tau τ^- have corresponding neutrinos ν_e, ν_μ and ν_τ.

v Electron, muon and tau have electric charge of $-e$. Neutrinos are neutral.

v Neutrinos have *very tiny* masses.

v For neutrinos, only weak interactions have been observed so far.

à Antileptons are positron e^+, positive muon and positive tau (***mu-plus*** and ***tau-plus***), and antineutrinos:

$$\begin{pmatrix} e^{+} \\ \bar{\nu}_{e} \end{pmatrix}, \begin{pmatrix} \mu^{+} \\ \bar{\nu}_{\mu} \end{pmatrix}, \begin{pmatrix} \tau^{+} \\ \bar{\nu}_{\tau} \end{pmatrix}$$

à Neutrinos and antineutrinos differ by the *lepton number*. Leptons posses lepton numbers $L_\alpha=1$ (α stands for e, μ or τ), and antileptons have $L_\alpha= -1$.

à Lepton numbers are conserved in all interactions.

Neutrinos can not be directly registered by any detector, there are only indirect measurements of their properties.

v First indication of neutrino existence came from β-decays of a nucleus N:

$$N(Z,A) \rightarrow N(Z+1,A) + e^{-} + \bar{\nu}_{e}$$

β-decay is nothing but a neutron decay:

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

observed, best fit result for the mass difference is

$\Delta m_{ij}^2 = (10^{-4}-10^{-5})\mathrm{eV}^2/c^4$ [$\Delta m_{ij}^2 = m_i^2 - m_j^2$, $i=e$, $j=\mu,\tau$]

à An inverse β-decay also takes place:

$$\nu_e + \mathrm{n} \rightarrow \mathrm{e}^- + \mathrm{p} \tag{22}$$

or

$$\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n} \tag{23}$$

However, the probability of these processes is very low, therefore to register it one needs a very intense flux of neutrinos

Reines and Cowan experiment (1956)

v Using antineutrinos produced in a nuclear reactor, it is possible to obtain around 2 events (10) per hour.

To separate the signal from the background, the

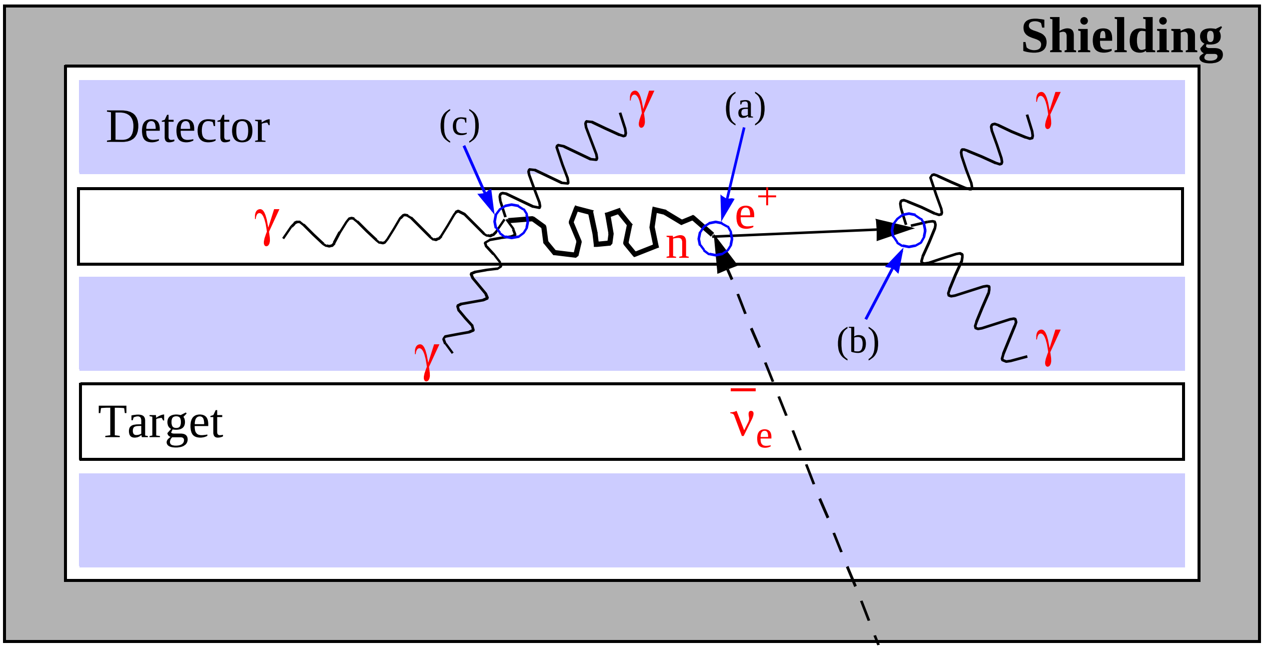

Figure 13: Schematic representation of the Reines and Cowan experiment. Aqueous solution of $CdCl_2$ used as the target (*Cd* used to capture neutrons).

“delayed coincidence” scheme was used: signal from neutron comes later than one from positron.

(a) $\bar{\nu}_e$ interacts with p, producing n and e^+

(b) e^+ annihilates with an atomic e^-, produces fast γ → softer γ ‘s through the Compton effect

(c) n captured by a *Cd* nucleus, releasing more γ ‘s.

à Muons were first observed in 1936, in *cosmic rays*

Cosmic rays have two components:

1) *primaries*, which are high-energy particles coming from the outer space, mostly hydrogen nuclei

2) *secondaries*, the particles which are produced in collisions of primaries with nuclei in the Earth atmosphere; muons belong to this component

v Muons are 200 times heavier than electrons and are very penetrating particles.

v Electromagnetic properties of muon are identical to those of electron (except the mass difference)

à Tau is the heaviest lepton, discovered in e^+e^- annihilation experiments in 1975

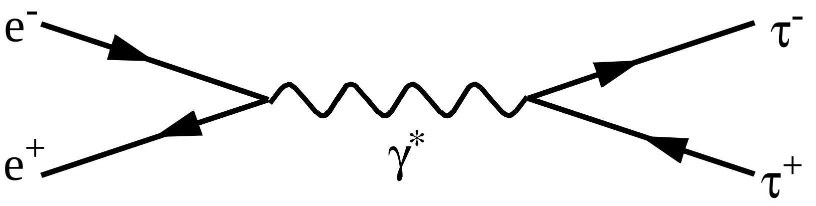

Figure 14: τ pair production in e^+e^- annihilation

à Electron is a stable particle, while muon and tauon have a finite lifetime:

$\tau_\mu = 2.2$ 5 10^{-6} s and $\tau_\tau = 2.9$ 5 10^{-13} s

Muon decays in a purely leptonic mode:

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu \tag{24}$$

Tau has a mass sufficient to decay into hadrons, but it has leptonic decay modes as well:

$$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau \tag{25}$$

$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau \tag{26}$$

à Fraction of a particular decay mode with respect to all possible decays is called *branching ratio*.

Branching ratio of the process (25) is 17.84%, and of (26) -- 17.37%.

à Note: lepton numbers are conserved in all reactions ever observed

Important assumptions:

1) Weak interactions of leptons are identical, just like electromagnetic ones (*“universality of weak interactions”*)

2) One can neglect final state lepton masses for many basic calculations

The *decay rate* Γ of a muon is given by expression:

$$\Gamma(\mu^- \to e^- + \bar{\nu}_e + \nu_\mu) = \frac{G_F^2 m_\mu^5}{195\pi^3} \tag{27}$$

where Γ=B/τ, τ=muon lifetime, B=branching ratio, and G_F is the *Fermi constant*.

Substituting m_μ with m_τ in (27), one obtains decay rates of tau leptonic decays. Since only m_τ appears in (27), decay rates are equal for processes (25) and (26). It explains why branching ratios of these processes have very close values.

Using the decay rate, the lifetime of a lepton is:

$$\tau_l = \frac{B(l^- \to e^- \bar{\nu}_e \nu_l)}{\Gamma(l^- \to e^- \bar{\nu}_e \nu_l)} \tag{28}$$

Here l stands for μ or τ . Since muons have basically only one decay mode, B=1 in their case. Using experimental values of B and formula (27), one obtains the ratio of muon and tau lifetimes:

$$\frac{\tau_\tau}{\tau_\mu} \approx 0{,}178 \cdot \left(\frac{m_\mu}{m_\tau}\right)^5 \approx 1{,}3\times10^{-7}$$

This again is in a very good agreement with independent experimental measurements

à Universality of lepton interactions is proved to a great extent. That means that there is basically no difference between lepton generations, **apart of the mass and the lepton numbers**.

à *Quarks* are spin-1/2 fermions, subject to all interactions. Quarks have fractional electric charges.

Quarks and their bound states are the only particles which interact strongly.

Some historical background:

v Proton and neutron ("nucleons") were known to interact strongly.

v In 1947, in cosmic rays, new heavy particles were detected (“hadrons”).

v By 1960s, in accelerator experiments, many dozens of hadrons were discovered

v An urge to find a kind of “periodic system” lead to the “Eightfold Way” classification, invented by Gell-Mann and Ne‘eman in 1961, based on the SU(3) symmetry group and describing hadrons in terms of “building blocks”.

v In 1964, Gell-Mann invented quarks as the building blocks (and Zweig invented “aces”).

à The quark model: *baryons* and *antibaryons* are bound states of three quarks, and *mesons* are bound states of a quark and antiquark.

à Hadrons = baryons and mesons.

Like leptons, quarks occur in three generations:

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$$

Corresponding antiquarks are:

$$\begin{pmatrix} \bar{d} \\ \bar{u} \end{pmatrix}, \begin{pmatrix} \bar{s} \\ \bar{c} \end{pmatrix}, \begin{pmatrix} \bar{b} \\ \bar{t} \end{pmatrix}$$

Name (“Flavour”)	**Symbol**	**Charge (units of e)**	**Mass**
Down	d	-1/3	5-8.5 **MeV/c^2**
Up	u	+2/3	1.5-4.5 **MeV/c^2**
Strange	s	-1/3	80-155 **MeV/c^2**
Charmed	c	+2/3	1.0-1.4 **GeV/c^2**
Bottom	b	-1/3	4.0-4.5 **GeV/c^2**
Top	t	+2/3	≈ 174 **GeV/c^2**

à Free quarks can never be observed

There is an elegant explanation for this:

à Every quark possesses a new quantum number: the *colour*. There are three different colours, thus each quark can have three distinct colour states. Colours are called *red (R)*, *green (G)* and *blue (B).*

à Coloured objects can not appear as free particles.

à Therefore quarks must confine into colourless hadrons.

à Colourless combinations: 3 colour states RGB ($\bar{R}\bar{G}\bar{B}$), or colour-anticolour ($R\bar{R}$, $G\bar{G}$, $B\bar{B}$, and their linear combinations).

Baryons are bound states of three quarks of different colours. Mesons consist of colour-anticolour quark pairs.

s-, c-, b- and top quarks have their own quantum numbers: *strangeness* S, *charm* C, *beauty* $\tilde{B}$ and *truth* T. These quantum numbers are conserved in strong and e.m. interactions, but not in weak ones.

Some examples of baryons:

Particle	**Mass (GeV/c^2)**	**Quark composition**	**Q (units of e)**	S	C	$\tilde{B}$
p	0.938	uud	1	0	0	0
n	0.940	udd	0	0	0	0
Λ	1.116	uds	0	-1	0	0
Λ_c	2.285	udc	1	0	1	0

Quark quantum numbers are defined as: *S*= -1 for s-quark, S=1 for $\bar{s}$; C=1 for c-quark; $\tilde{B}$= -1 for b-quark, T=1 for t-quark.

The top-quark has a very short lifetime, so it doesn't form hadrons before decaying → T=0 for all hadrons.

Quark numbers for u- and d-quarks have no name, but just like the other flavours, they are conserved in strong and electromagnetic interactions.

Baryons are assigned own quantum number B: B=1 for baryons, B=-1 for antibaryons and B=0 for mesons. $B=1/3\,[N(q)-N(\bar{q})]$, where $N(q)$ and $N(\bar{q})$ are the total number of quarks and antiquarks present.

à Baryon number is conserved in all interactions → the lightest baryon, proton, is stable.

Some examples of mesons:

Particle	**Mass (Gev/c^2)**	**Quark composition**	**Q (units of e)**	S	C	$\tilde{B}$
π^+	0.140	$u\bar{d}$	1	0	0	0
K^-	0.494	$s\bar{u}$	-1	-1	0	0
D^-	1.869	$d\bar{c}$	-1	0	-1	0
D_s^+	1.969	$c\bar{s}$	1	1	1	0
B^-	5.279	$b\bar{u}$	-1	0	0	-1
Y	9.460	$b\bar{b}$	0	0	0	0

- Majority of hadrons are unstable and tend to decay by the strong interaction to the state with the lowest possible mass (lifetime about 10^{-23} s).

- Hadrons with the lowest possible mass for each quark number (*S*, *C*, etc.) may live significantly longer before decaying weakly (lifetimes 10^{-7}-10^{-13} s) or electromagnetically (mesons, lifetimes 10^{-16} - 10^{-21} s). Such hadrons are called *long-lived particles*.

- The only stable hadron = proton.

Brief history of hadron discoveries

v First known hadrons were proton and neutron.

v The lightest are pions (π = pi-mesons). There are charged pions π^+, π^- with mass of 0.140 GeV/c^2, and neutral ones π^0, mass 0.135 GeV/c^2.

à Pions and nucleons are the lightest particles containing u- and d-quarks only.

Pions were discovered in 1947 in cosmic rays, using photoemulsions to detect particles.

Some reactions induced by cosmic rays primaries:

$$\begin{aligned} p + p &\to p + n + \pi^+ \\ &\to p + p + \pi^0 \\ &\to p + p + \pi^+ + \pi^- \end{aligned}$$

Same reactions can be reproduced in accelerators, with higher rates, although cosmic rays may provide higher energies.

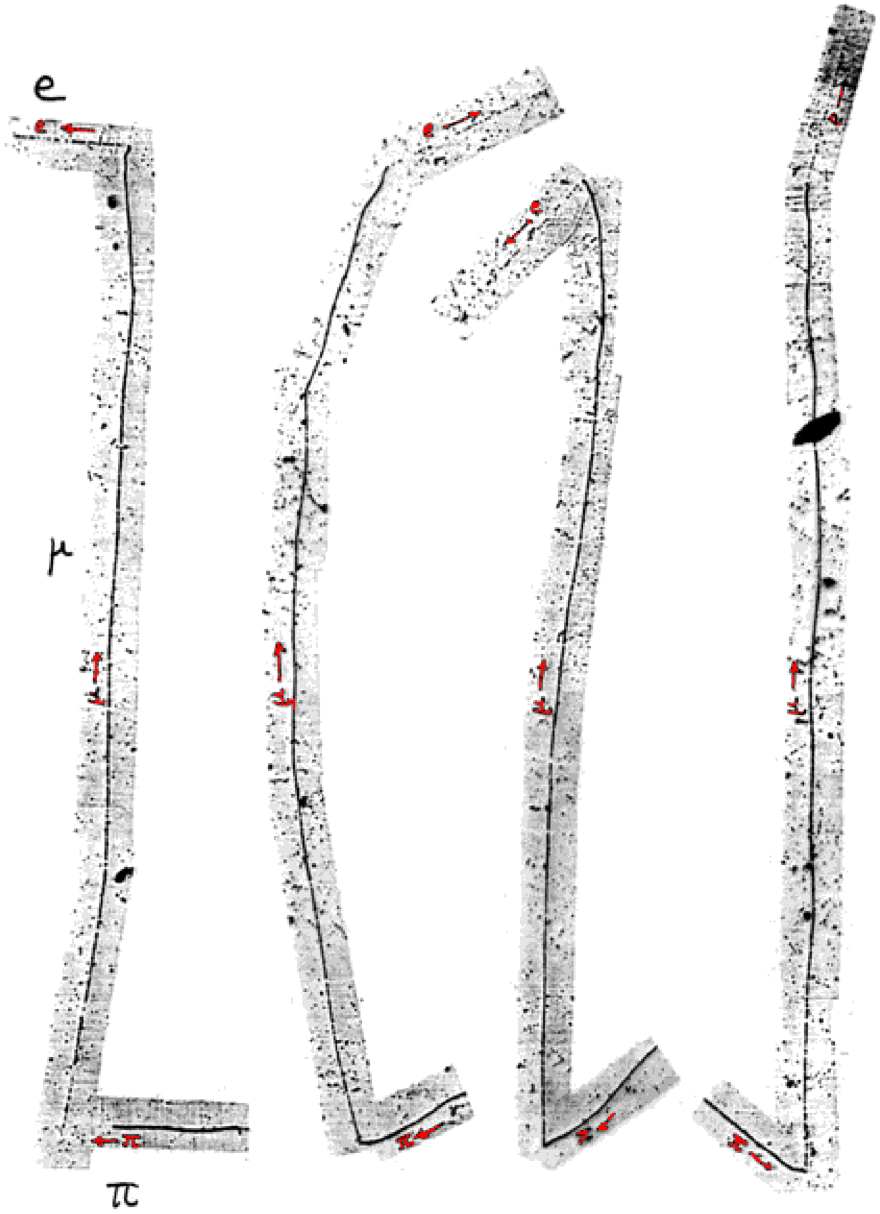

Figure 15: First observed pions: a π^+ stops in the emulsion and decays to a μ^+ and ν_μ, followed by the decay of μ^+.In emulsions, pions were identified by much more dense ionization along the track, as compared to electron tracks.

Figure 15 shows examples of the reaction

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad (29)$$

where the pion comes to the rest, producing muons which in turn decay by the reaction $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$.

à Charged pions decay mainly to the muon-neutrino pair (branching ratio about 99.99%), having lifetimes of 2.6 x 10^{-8} s. In quark terms:

$$(u\bar{d}) \rightarrow \mu^+ + \nu_\mu$$

The decay occurs through weak interactions (annihilation of $u\bar{d}$ into W^+ boson): note that weak interactions do not conserve quark quantum numbers! *B* and *L* are, however, conserved.

à Neutral pions decay mostly by the electromagnetic interaction, having shorter lifetime of 0.8 x 10^{-16} s:

$$\pi^0 \rightarrow \gamma + \gamma$$

Discovered pions were fitting very well into Yukawa's theory -- they were supposed to be responsible for the nuclear forces:

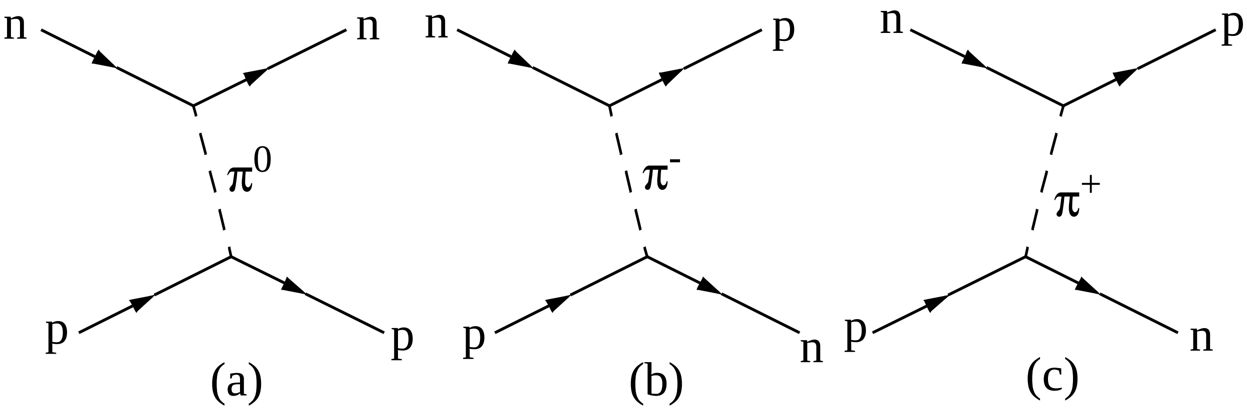

Figure 16: Yukawa model of direct (a) and exchange (b,c) nuclear forces

- The resulting potential for this kind of exchange is of Yukawa type (19), and at the longest range reproduces observed nuclear forces very well, including even spin effects.

- However, at the ranges comparable with the size of nucleons, this description **fails**, and the internal structure of hadrons must be taken into account.

Strange mesons and baryons

were called so, because they were produced in strong interactions, but they had nevertheless quite long lifetimes, and they decayed weakly.

The lightest particles containing s-quarks are:

- mesons K^+, K^- and K^0, $\bar{K}^0$: *"kaons"*, lifetime of K^+ is 1.2×10^{-8} s
- baryon Λ, lifetime of 2.6×10^{-10} s

Principal decay modes of strange hadrons:

$$K^+ \rightarrow \mu^+ + \nu_\mu \qquad (B=0.64)$$

$$K^+ \rightarrow \pi^+ + \pi^0 \qquad (B=0.21)$$

$$\Lambda \rightarrow \pi^- + p \qquad (B=0.64)$$

$$\Lambda \rightarrow \pi^0 + n \qquad (B=0.36)$$

The first decay in the list is clearly a weak one. Decays of Λ could be very well described as strong ones if they did not have such a long lifetime (10^{-10} s). If Λ were (udd), the decay *(udd)* $\rightarrow$ *$(d\bar{u})$* + *(uud)* should have a lifetime of order 10^{-23} s. Therefore, Λ cannot be (udd) as the neutron...

Solution: to invent a new *"strange"* quark, bearing a new quark number -- *"strangeness"*, which does not have to be conserved in weak interactions

S=1	S=-1
$\overline{\Lambda}(1116) = \overline{uds}$	$\Lambda(1116) = uds$
$K^+(494) = u\bar{s}$	$K^-(494) = s\bar{u}$
$K^0(498) = d\bar{s}$	$\overline{K}^0(498) = s\bar{d}$

à In strong interactions, strange particles have to be produced in pairs in order to conserve total strangeness (*"associated production"*):

$$\pi^- + p \rightarrow K^0 + \Lambda \qquad (30)$$

In 1952, *bubble chambers* were invented as particle detectors, and also worked as *targets*, providing, for instance, the proton target for reaction (30).

How does a bubble chamber work:

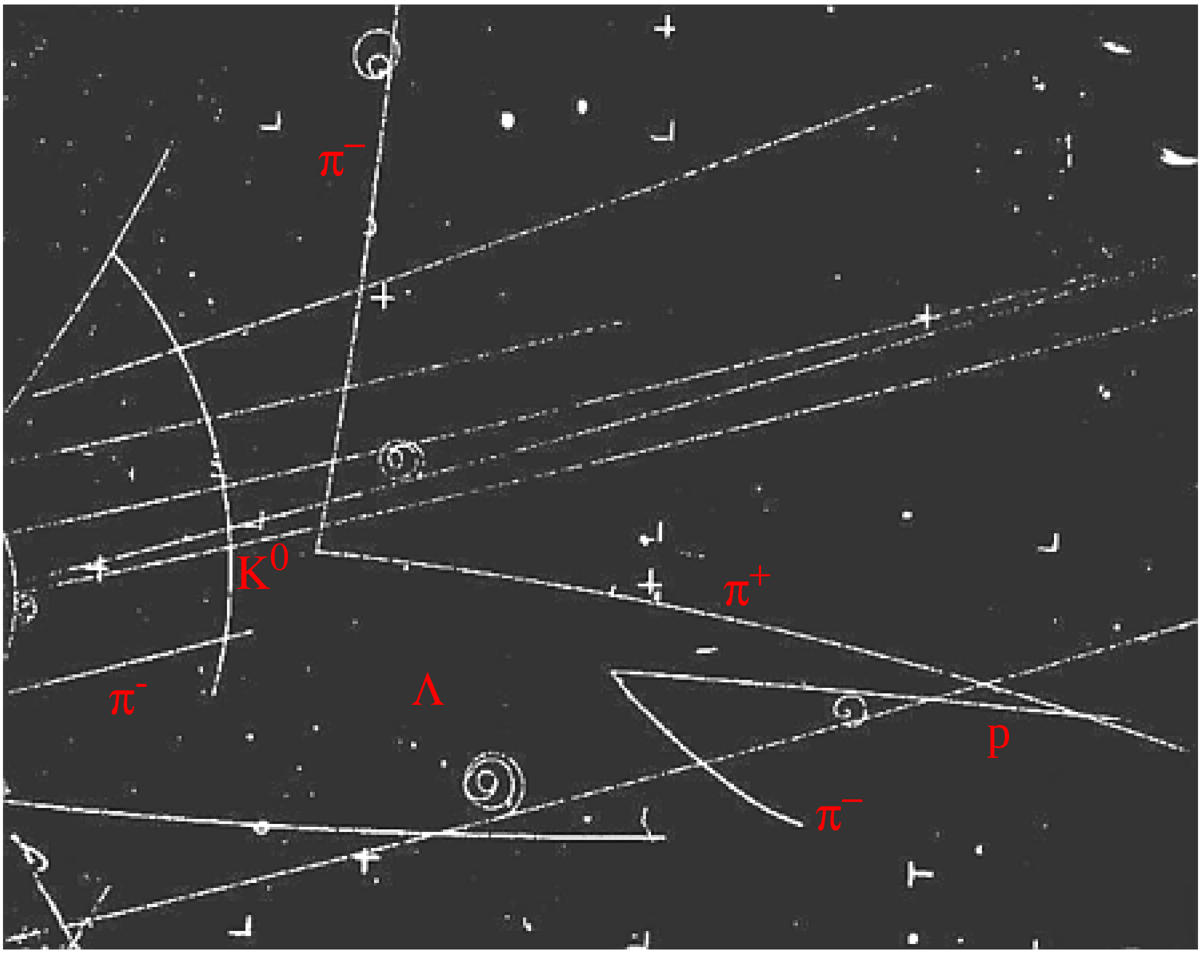

Figure 17: A bubble chamber picture of the reaction (9)

– It is filled with a liquid (hydrogen, propane, freons) under pressure, heated above its boiling point.

– Particles ionize the liquid along their passage.

– Volume is expanded → pressure drops → liquid starts boiling along the ionization trails.

– Visible bubbles are stereo-photographed.

v Bubble chambers were great tools in particle discoveries, providing physicists with numerous hadrons, all of them fitting u-d-s quark scheme until 1974.

- In 1974, a new particle was discovered, which demanded a new flavour to be introduced. Since it was detected simultaneously by two groups in Brookhaven (BNL) and Stanford (SLAC), it received a double name: J/ψ (3097) = $c\bar{c}$

The new quark was called *"charmed"*, and the corresponding quark number is *charm*, *C*. Since J/ψ itself has C=0, it is said to contain "hidden charm".

Shortly after that particles with "open charm" were discovered as well:

$$D^+(1869) = c\bar{d},\ D^0(1865) = c\bar{u}$$
$$D^-(1869) = d\bar{c},\ \bar{D}^0(1865) = u\bar{c}$$

$$\Lambda_c^+(2285) = udc$$

Even heavier charmed mesons were found -- those which contained strange quark as well:

$$D_s^+(1969) = c\bar{s},\ D_s^-(1969) = s\bar{c}$$

Lifetimes of the lightest charmed particles are of order 10^{-13} s, well in the expected range of weak decays.

- Discovery of "charmed" particles was a triumph for the electroweak theory, which demanded number of quarks and leptons to be equal.

In 1977, *"beautiful"* mesons were discovered:

$$\Upsilon(9460) = b\bar{b}$$

$$B^+(5279) = u\bar{b},\ B^0(5279) = d\bar{b}$$

$$B^-(5279) = b\bar{u},\ \bar{B}^0(5279) = b\bar{d}$$

and the lightest b-baryon: $\Lambda_b^0(5461) = udb$

And this is the limit: top-quark is too unstable to form observable hadrons