Lecture 7 – Order in the particle ZOO

- *Wave description of particles → interference*

All components of the wave function must be the same, amplitudes may be different

- *Interference is true also for the force carriers with similar properties: Z and γ*
- *Many (several hundred) "resonance states" observed*

π^+, π^-, π^0, K^+, K^-, K^0, $K^*(890)$, $K^*(1420)$, N^*, Λ^0, Σ^+, Σ^-, Ξ........

→ *1964 -* ***Gell-Mann + Zweig*** *proposed Quark Model: all elementary particles are made from smaller constituents called quarks.*

Until 1975 - All of the strongly interacting particles are composites of 3 quarks : u-up, d-down, s- strange

After 1975 – expanded to six quarks generically called flavors:

u – up, d – down, s – strange, c – charm, b – bottom, t –top

All quarks have the corresponding antiquarks with opposite charges,

baryons: proton, neutron,.... are made out of 3 quarks

mesons: π, K, ρ, ψ ..... are made out of quark – antiquark pairs

- *In order to understand the Model we must first discuss the conservation laws*

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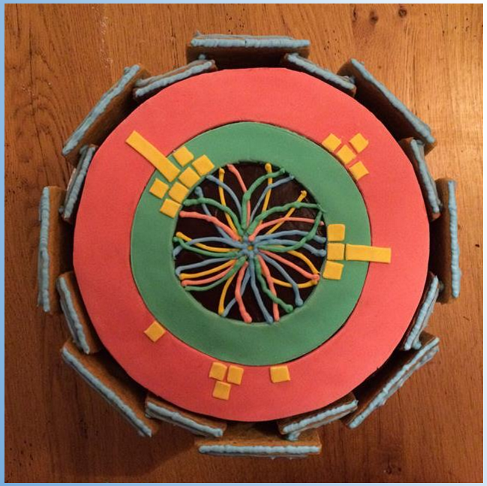

Tuesday September 8th

6:30 PM

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Conservation laws

- *All massive particle, unless prevented by some rule, decay into lighter particles.*
- *Massless particles (photons) or very light particles (electrons, neutrinos) do not decay because all other particles are heavier.*
- *There are several general rules that come from mechanics and electromagnetic interactions:*
- *These conservation laws are:*
  - *conservation of energy*
  - *conservation of momentum*
  - *conservation of angular momentum*
  - *conservation of charge*
- *If a particle decay is allowed by the above, but is not observed, we invent new conservation laws. Baryon (3 quark states) number conservation is an example of such law. Very unsatisfactory !*

CONSERVED QUANTUM NUMBERS

Why is the free proton stable?

Possible proton decay modes (allowed by all known conservation laws: energy – momentum, electric charge, angular momentum):

$$p \rightarrow \pi^{\circ} + e^{+}$$
$$p \rightarrow \pi^{\circ} + \mu^{+}$$
$$p \rightarrow \pi^{+} + \nu$$
$$\cdots\cdots$$

No proton decay ever observed – the proton is STABLE

Limit on the proton mean life depends on the assumed decay mode and date:

$\tau_p > 1.6 \times 10^{33}$ years for decays to μ^+ and $\tau > 1.3 \times 10^{34}$ years for decays to e^+

model dependent estimates are $\tau_p \sim 10^{32}$ years

Invent a new quantum number : "Baryonic Number" B

B = 1 for proton, neutron

B = -1 for antiproton, antineutron

B = 0 for $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$, neutrinos, mesons, photons

Require conservation of baryonic number in all particle processes:

$$\sum_i B_i = \sum_f B_f$$

(***i*** **:** initial state particle ; ***f*** **:** final state particle; include all "resonant and long lived" states)

Baryon number conservation rule extends to all excited states of objects consisting of 3 quarks.
These include N states with half-integer spins ranging from ½ to 11/2 with masses extending to 2600 MeV. In addition all baryon type particles (3 valence quarks) that contain strange and heavy quark (Λ, Δ, Ξ,…) also obey this rule. In the last few years barions containing charm quarks have also been found.*

Comment on frequency of production and lifetime

Recall relative strength of strong, electromagnetic and weak interactions. In e.g., proton-proton collisions there is an abundant production of mesons and both baryonic and mesonic resonances. The resonances decay at a time scale of 10^{-23} s that we consider a typical time scale of strong interactions.
The electromagnetic decays e.g., π^0 decay to two photons has a typical lifetime of $\sim 10^{-17}$ s
The characteristic lifetime of particles decaying due to weak interactions is $\sim 10^{-6} \div 10^{-8}$ s. These are called "long-lived" particles.
Particles may be subject to any type of interactions.
That means that they may have both strong and weak decays. The corresponding decay branching fractions will be inversely proportional to the ratio of the relative strength of strong and weak interactions.

Conserved quantities: energy, momentum, angular momentum

always

Conserved quantum numbers: baryon number, strangeness, ...

in production (collision)

Particles can be produced by strong interactions

eg. pair of K mesons with opposite strangeness:

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

the same particles can then decay via weak interactions

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

both processes have characteristic associated time

(Once produced the particle does not remember how it was created.)

Consequence – strong interactions conserve more "quantum numbers" then weak interactions.

Isospin
The quark model

There is an approximate "symmetry" that applies to strong interactions.

isospin or isotopic spin

It was useful in formulation of the quark picture of known particles.

We can consider groups of particles that differ mostly by their charge as different states of the same particle. e.g., proton and neutron, or 3 states of a pion π^+, π^-, π^0. These particles are equally affected by the strong force. The isospin is treated as if it would be a quantum mechanical angular momentum with its third component I_3 related to an electric charge.

For nucleon: $Q = ½ + I_3$ *where one may consider proton and neutron to be two states of the same particle that may have values of $I_3 = -1/2$ or $+1/2$ giving the charge assignment of 0 or +1. Similar considerations can be used for π meson that comes with three charges: -1, 0 and +1. It has an assigned isospin =1 with three projections and charge $Q = I_3$*

THE "STATIC" QUARK MODEL

Late 1950's – early 1960's: discovery of many strongly interacting particles at the high energy proton accelerators (Berkeley Bevatron, BNL AGS, CERN PS), all with very short mean life times (10^{-20} – 10^{-23} s, typical of strong decays)

→ catalog of > 100 strongly interacting particles (collectively named "hadrons")

ARE HADRONS ELEMENTARY PARTICLES?

1964 (Gell-Mann, Zweig): Hadron classification into "families"; observation that all hadrons could be built from three spin ½ "building blocks" (named "quarks" by Gell-Mann):

	u	d	s
Electric charge (units $\|e\|$)	+2/3	–1/3	–1/3
Baryonic number	1/3	1/3	1/3
Strangeness	0	0	–1

and three antiquarks ($\bar{u}$, $\bar{d}$, $\bar{s}$) with opposite electric charge and opposite baryonic number and strangeness

Mesons: quark – antiquark pairs

Examples of non-strange mesons:

$$\pi^+ \equiv u\bar{d} \quad ; \quad \pi^- \equiv \bar{u}d \quad ; \quad \pi^0 \equiv (d\bar{d} - u\bar{u})/\sqrt{2}$$

Examples of strange mesons:

$$K^- \equiv s\bar{u} \quad ; \quad \overline{K}^0 \equiv s\bar{d} \quad ; \quad K^+ \equiv \bar{s}u \quad ; \quad K^0 \equiv \bar{s}d$$

Baryons: three quarks bound together
Antibaryons: three antiquarks bound together

Examples of non-strange baryons:

$$\text{proton} \equiv uud \quad ; \quad \text{neutron} \equiv udd$$

Examples of strangeness –1 baryons:

$$\Sigma^+ \equiv suu \quad ; \quad \Sigma^0 \equiv sud \quad ; \quad \Sigma^- \equiv sdd$$

Examples of strangeness –2 baryons:

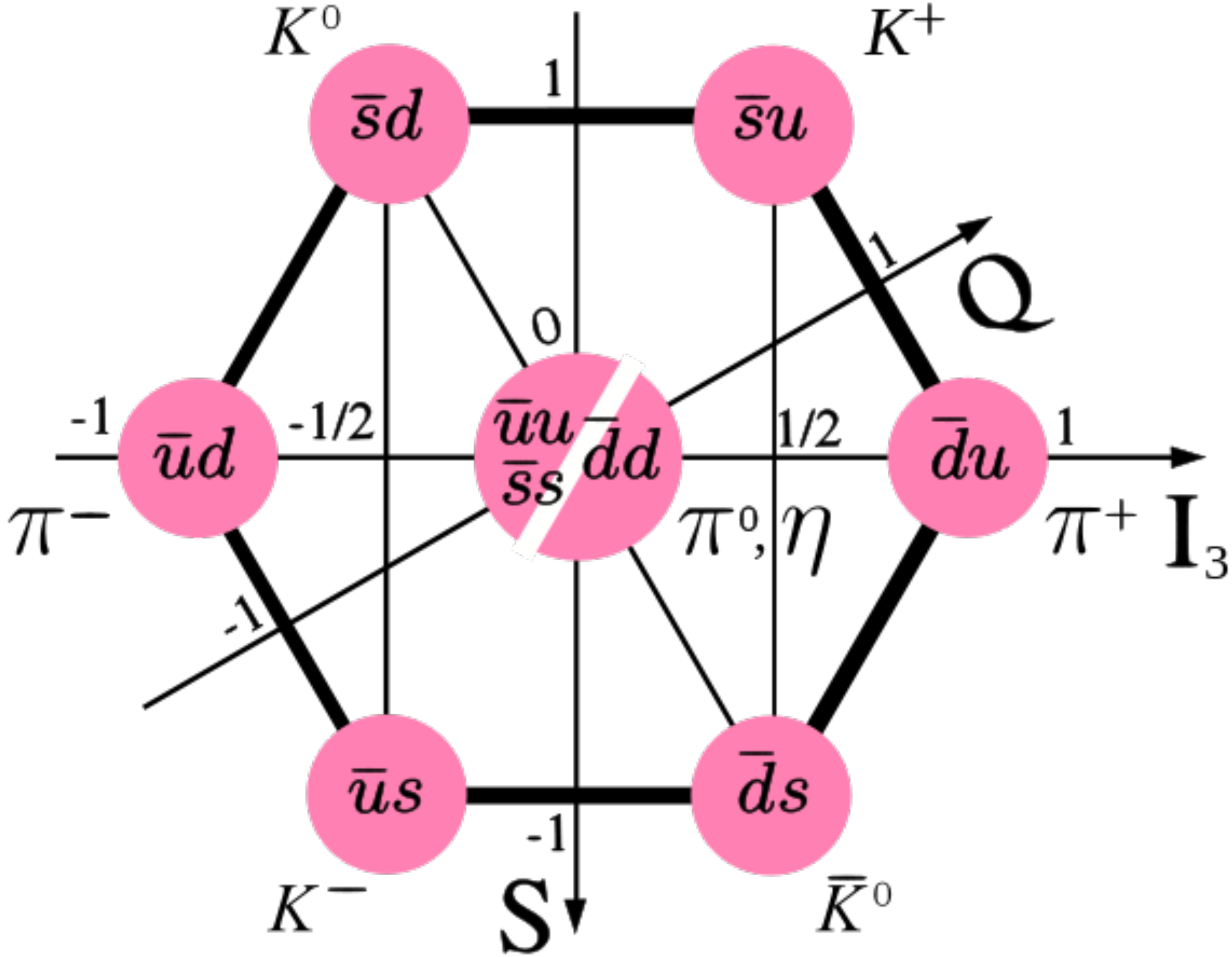
$$\Xi^0 \equiv ssu \quad ; \quad \Xi^- \equiv ssd$$

The pseudo-scalar meson octet

S=1

S=0

S=-1



•*All states in a given grouping have the same orbital momentum of quarks with respect to each other. The "octet" in the previous slide corresponds to l = 0 single spin state. The spin of the meson is due to the arrangement of the spins of the quarks. Recall that antiquarks have opposite parity to quarks so all mesons on the slide have spin J=0 and parity P=-1, these are pseudoscalar mesons. Their wave function changes sign under spatial inversion.*

•*Three types of quarks with spin =1/2 (u, d, s) should give 9 states quark – antiquark states. These are listed in the diagram by noticing that for two quarks u and d there are 4 possible combinations allowed if one includes isospin as a quantum number:*

$$\left.\begin{array}{ll} \pi^{\div} = u\bar{d} & isospin = +1 \\ \pi^{-} = \bar{u}d & isospin = -1 \\ \pi^{0} = \sqrt{1/2}(d\bar{d} - u\bar{u}) & isospin = 0 \end{array}\right\} \quad \textit{Isospin triplet}$$

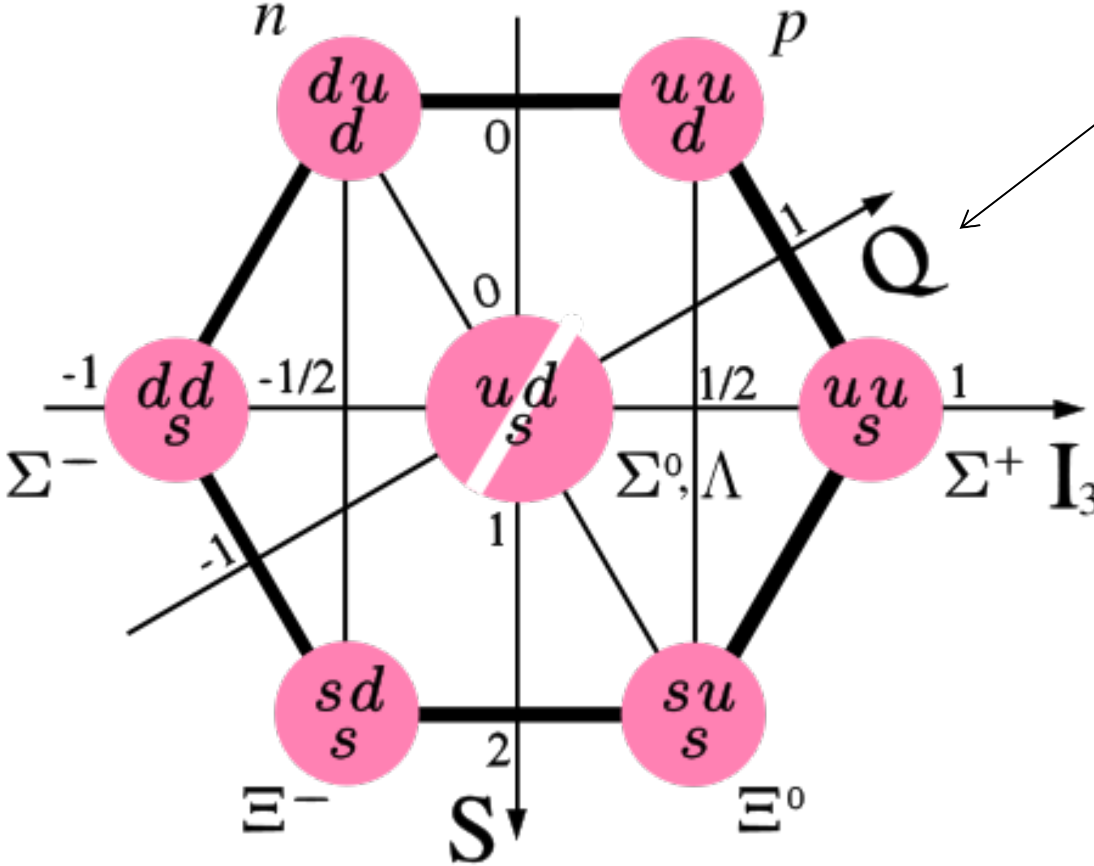
$$\eta = \sqrt{1/2}(d\bar{d} + u\bar{u}) \quad isospin = 0 \qquad \textit{Isospin singlet}$$

The baryon octet

S=0

S=-1

S=-2

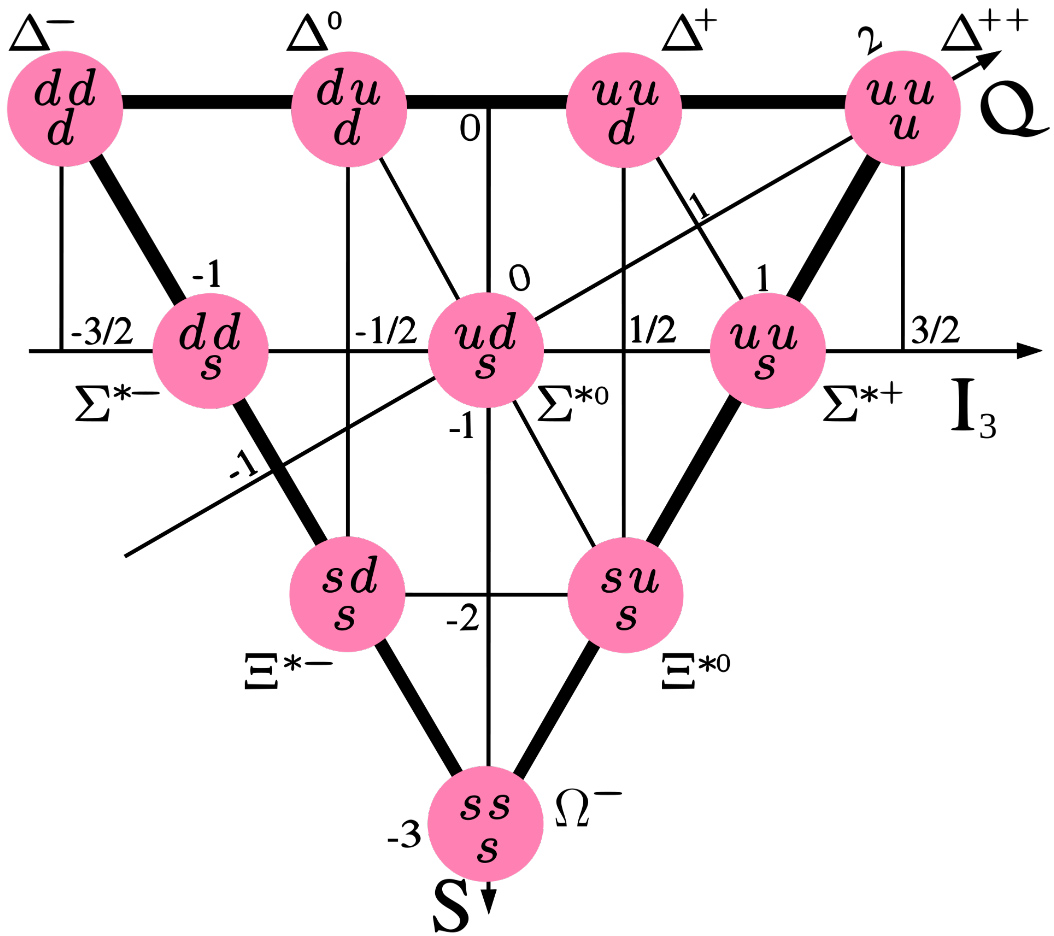


electric charge

isospin

strangeness

The baryon decuplet



Note: Δ is the original particle name, N* is its current name in spectroscopic notation.

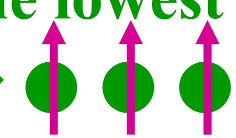
Prediction and discovery of the Ω^- particle

A success of the static quark model

The "decuplet" of spin $\frac{3}{2}$ baryons

Strangeness					Mass (MeV/c^2)
0	N^{*++} *uuu*	N^{*+} *uud*	$N^{*\circ}$ *udd*	N^{*-} *ddd*	1232
–1	Σ^{*+} *suu*	$\Sigma^{*\circ}$ *sud*	Σ^{*-} *sdd*		1384
–2	$\Xi^{*\circ}$ *ssu*	Ξ^{*-} *ssd*			1533
–3	Ω^- *sss*				1672 (predicted)

Ω^-: the bound state of three *s* – quarks with the lowest mass and with total angular momentum = 3/ 2 →



Pauli's exclusion principle requires that the three quarks cannot be identical ?

In all sets

- horizontal line determines strangeness

- diagonal line determines electric charge

Predicted characteristics of Ω^-

-charge = -1

- strangeness = -3

- mass expectation based on equal spacing between particles lying on horizontal lines the of leftmost diagonal (essentially mass difference due to change of u to s quark)

The first Ω^- event (observed in the 2 m liquid hydrogen bubble chamber at BNL using a 5 GeV/c K^- beam from the 30 GeV AGS in 1964)

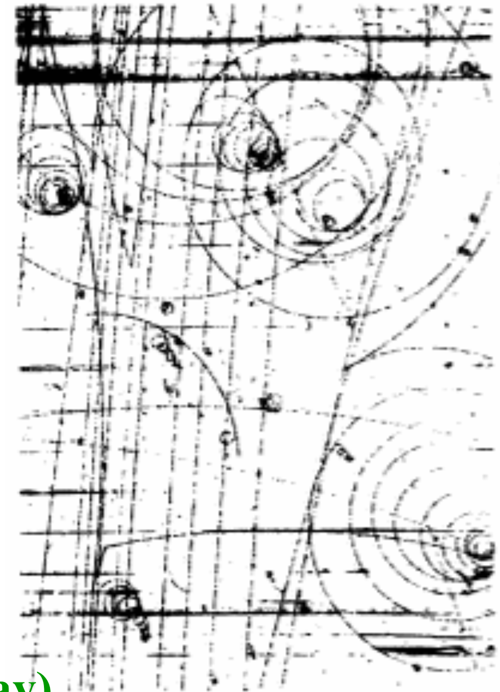
Chain of events in the picture:

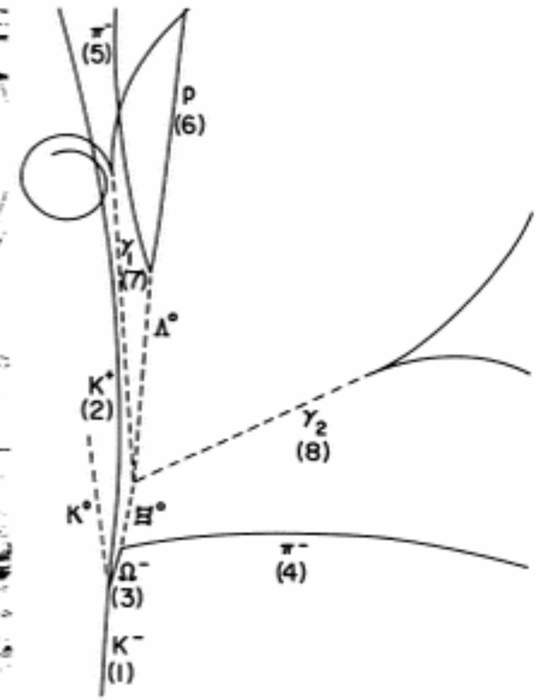
$K^- + p \rightarrow \Omega^- + K^+ + K^\circ$
(strangeness conserving)

$\Omega^- \rightarrow \Xi^\circ + \pi^-$
($\Delta S = 1$ weak decay)

$\Xi^\circ \rightarrow \pi^\circ + \Lambda$ ($\Delta S = 1$ weak decay)

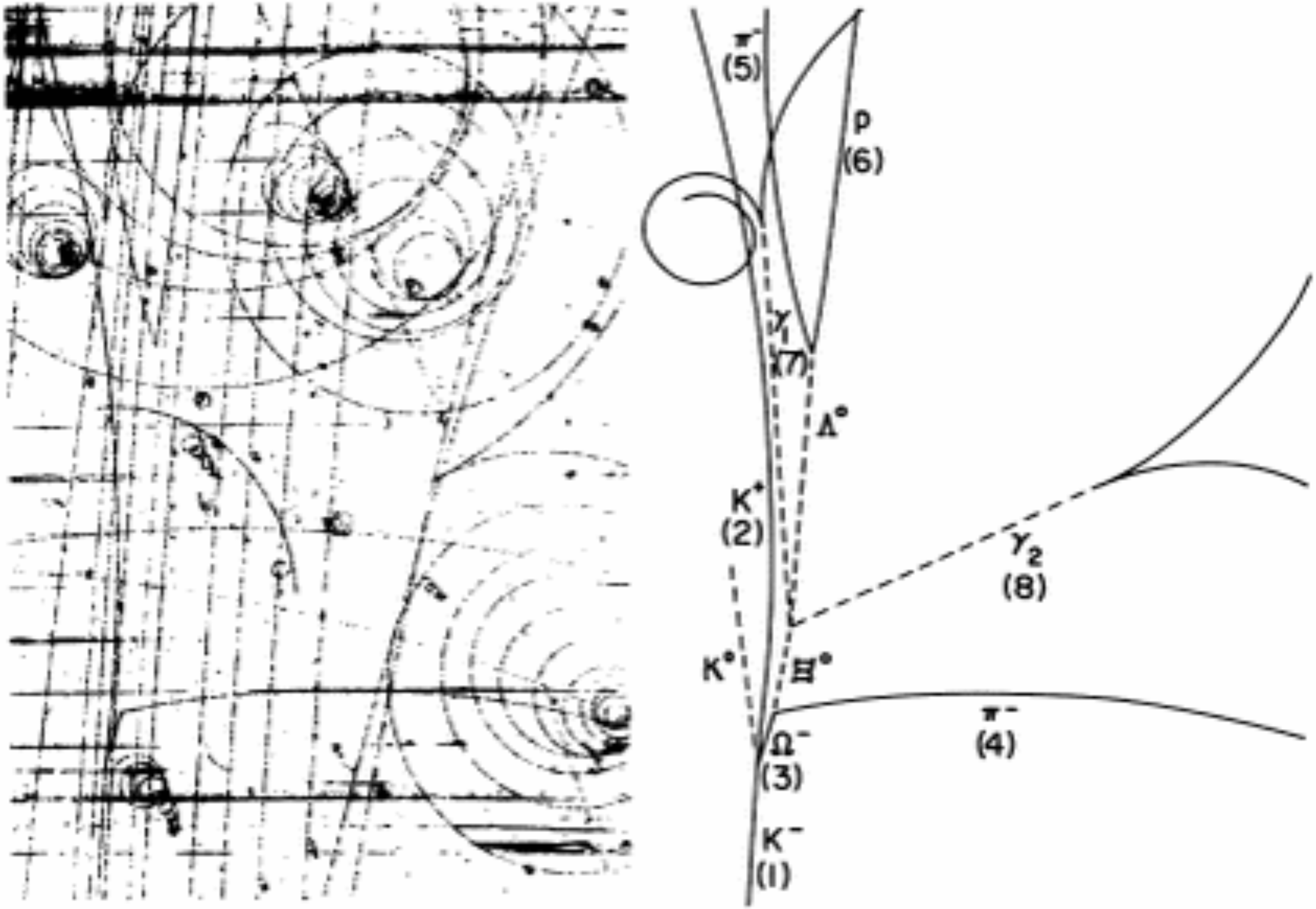
$\Lambda \rightarrow \pi^- + p$
($\Delta S = 1$ weak decay)





$\pi^\circ \rightarrow \gamma + \gamma$ (electromagnetic decay)
with both γ– rays converting to an e^+e^- in liquid hydrogen
(very lucky event, because the mean free path for $\gamma \rightarrow e^+e^-$ in liquid hydrogen is ~10 m)

Ω^- mass measured from this event = 1686 ± 12 MeV/c^2
(predicted mass = 1672 MeV/c^2)



π^-
(5)
p
(6)
γ_1
(7)
Λ^0
K^+
(2)
γ_2
(8)
K^0
Ξ^0
π^-
(4)
Ω^-
(3)
K^-
(1)

Discovery of Ω- was a great success.
Notice – this is only one event, statistically not significant, but all masses are well known so information is <u>over-constrained.</u>

What followed was a long and <u>unsuccessful</u> search for quarks – particles with fractional charges should leave traces with smaller ionization that that of an electron or muon.

At the same time theorist faced the problem of minimum charge needed for the quantization of the electromagnetic field.

There was one additional problem: Pauli principle forbids objects with the same quantum number to be in the same state. That means that the three quarks in Ω^- or Δ^{++} must be different from each other.

Consequence – Quark model became unpopular – it was thought to be just a nice mathematical tool for systematic of particles known at that time. Other mathematical models based on wave behavior came into fashion.