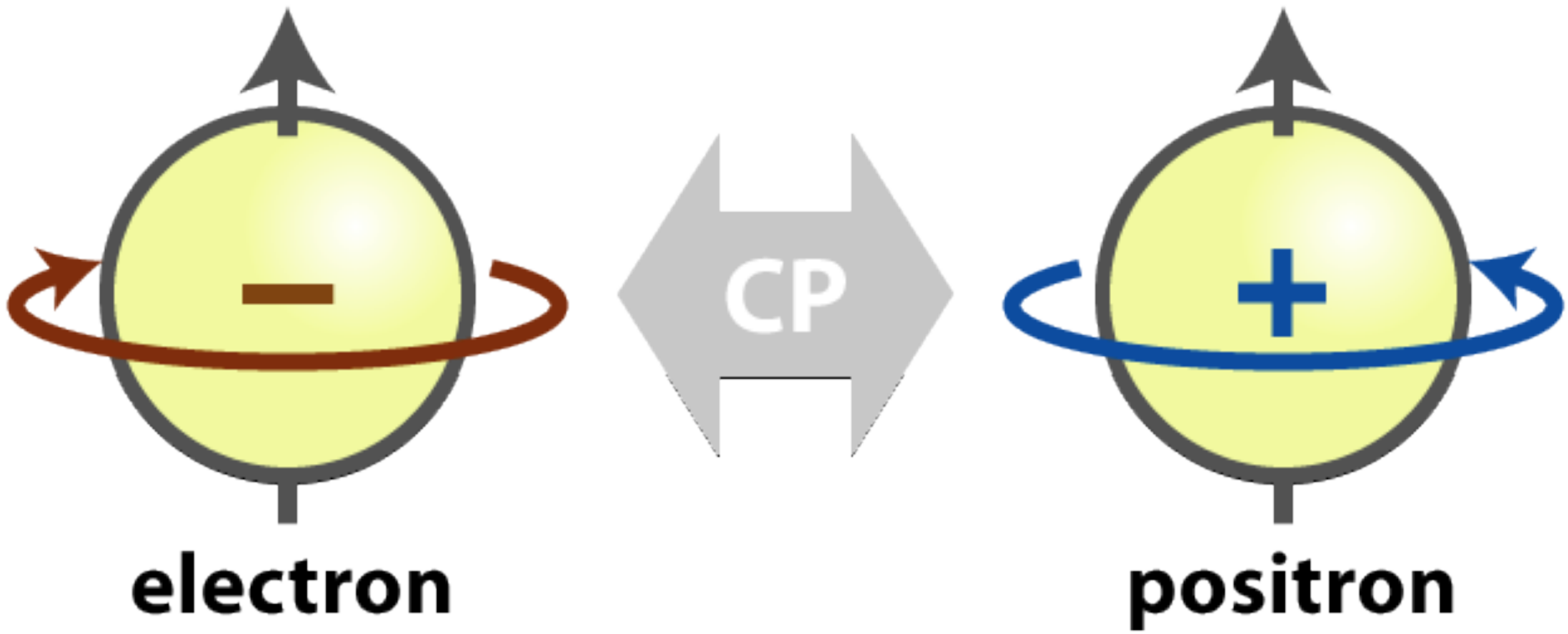
Lecture 8

CPT theorem and CP violation


CP
electron
positron

•*We have seen that although both charge conjugation and parity are violated in weak interactions, the combination of the two CP turns left-handed antimuon onto right-handed muon, that is exactly observed in nature.*

•*There is another symmetry in nature – time reversal T (winding the film backward).*

•*Charge conjugation, C, together with parity inversion, P, and time reversal, T, are connected into the famous CPT theorem.*

•*CPT theorem is one of the basic principles of quantum field theory. It states that all interactions are invariant under sequential application of C, P and T operations in any order.* ***Any Lorentz invariant local quantum field theory with a Hermitian Hamiltonian must have CPT symmetry.***

•*It is closely related to the interpretation that antiparticles can be treated mathematically as particles moving backward in time.*

Consider a Lorentz boost in a fixed direction z. This can be interpreted as a rotation of time axis into the z axis with an imaginary rotation parameter. If this rotation parameter were real, it would be possible for a 180^0 rotation to reverse the direction of time and of z. reversing the direction of one axis is a reflection of space in any number of dimensions. For a 3 dimensional space, it is equivalent to reflection of all the coordinates, because an additional rotation of 180^0 in the x-y plane would be included.

•*Symmetry of time reversal is very difficult to test experimentally. One of its prediction is that some properties of particles and antiparticles should have the same magnitudes, e.g., mass, lifetime, magnetic moment. For most of the cases that has been verified to be true within measurement precision, but not always.*

•*CPT theorem implies that the violation of CP invariance implies violation of time reversal symmetry T.*

•*One of the most important unresolved questions today is the evolution of the universe. If it started with a Big Bang where all interactions had strength of strong forces – then there should be equal amount of matter and antimatter in the universe. CP violation allows for some preference of survival of matter over survival of antimatter, but so far we have not seen sufficient amount of CP violation to account for observations of the Cosmos.*

Isospin
The quark model

There is one more "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:

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

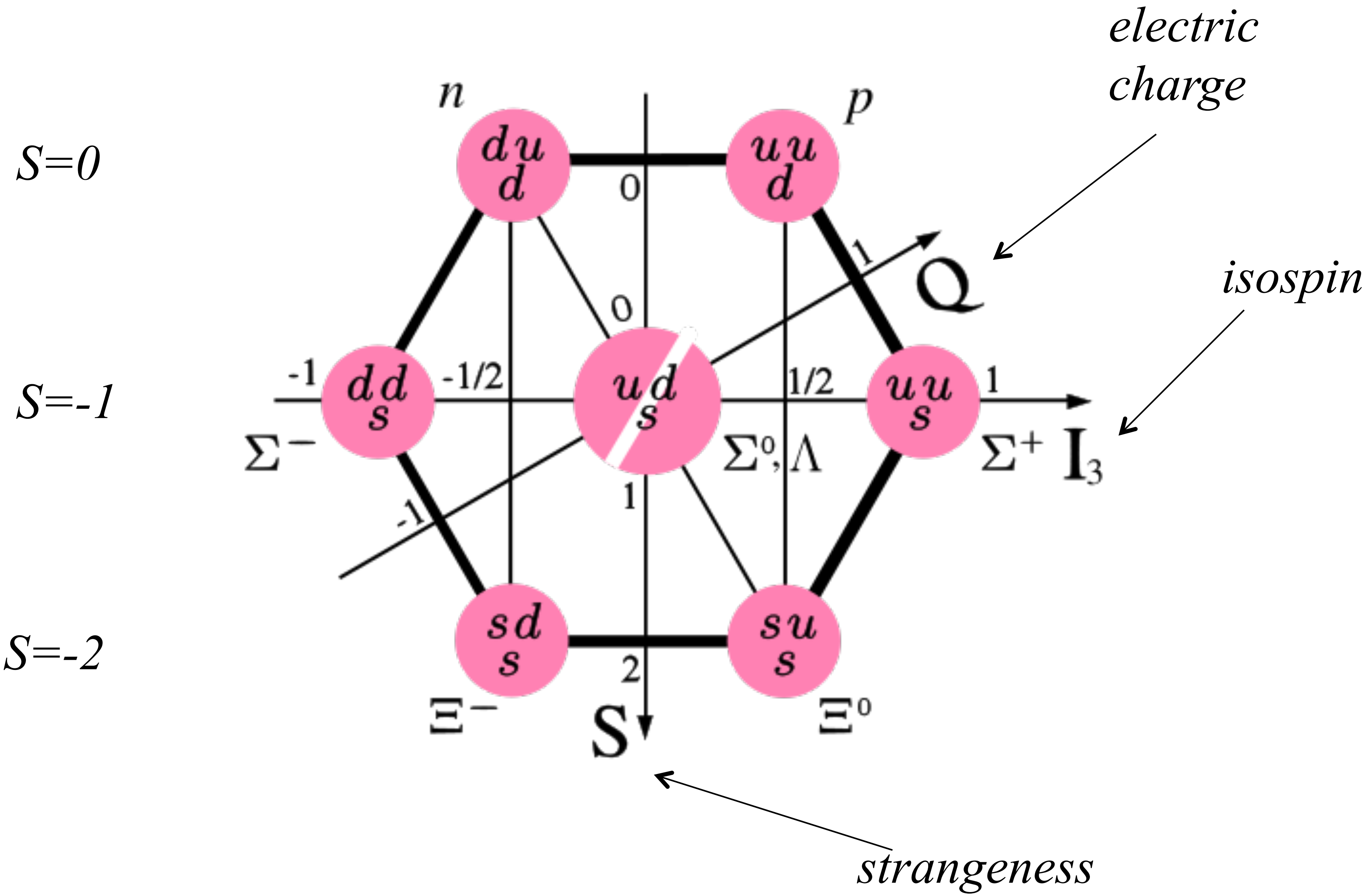
Examples of strangeness –1 baryons:

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

Examples of strangeness –2 baryons:

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

The baryon octet

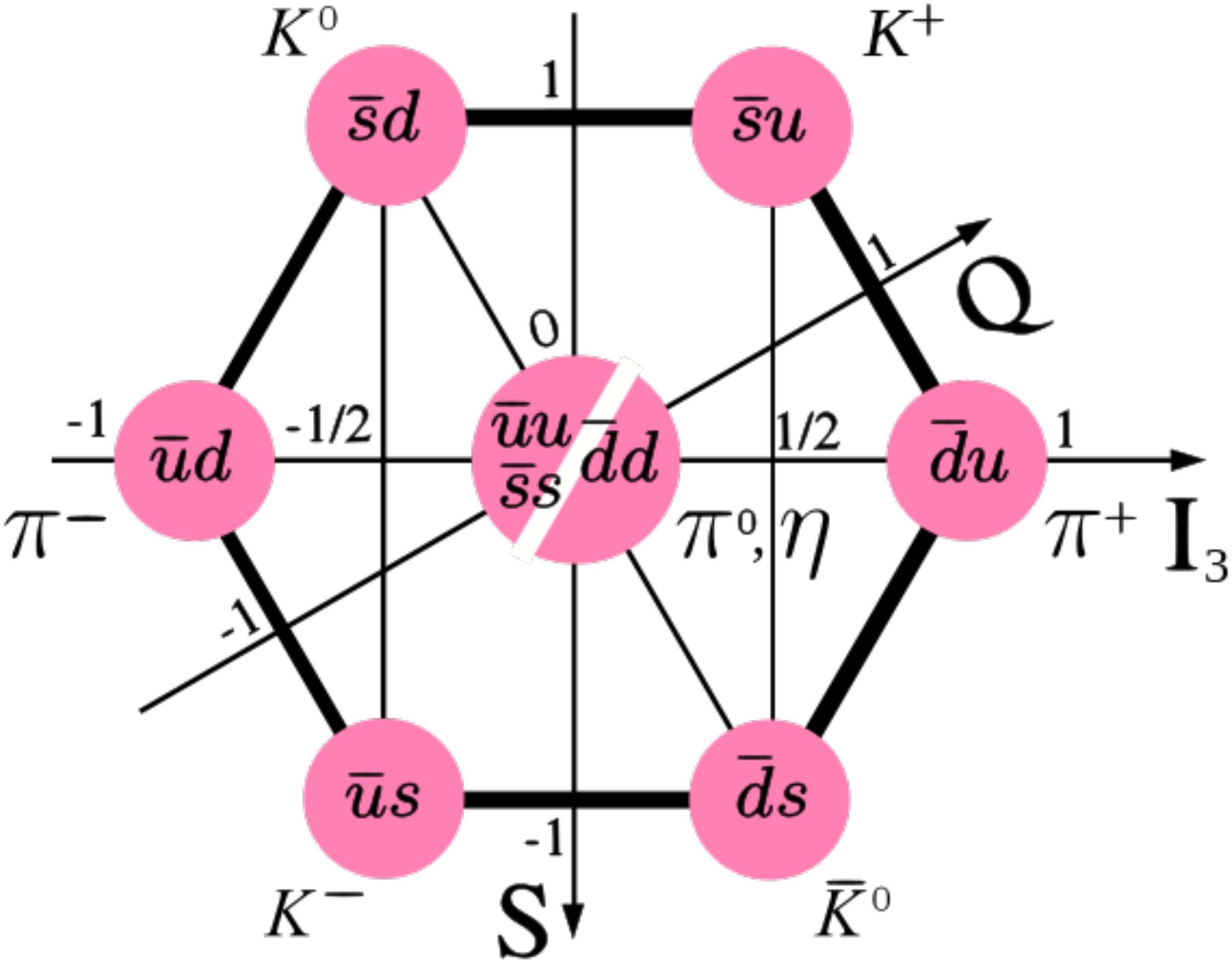


The pseudo-scalar meson octet

S=1

S=0

S=-1



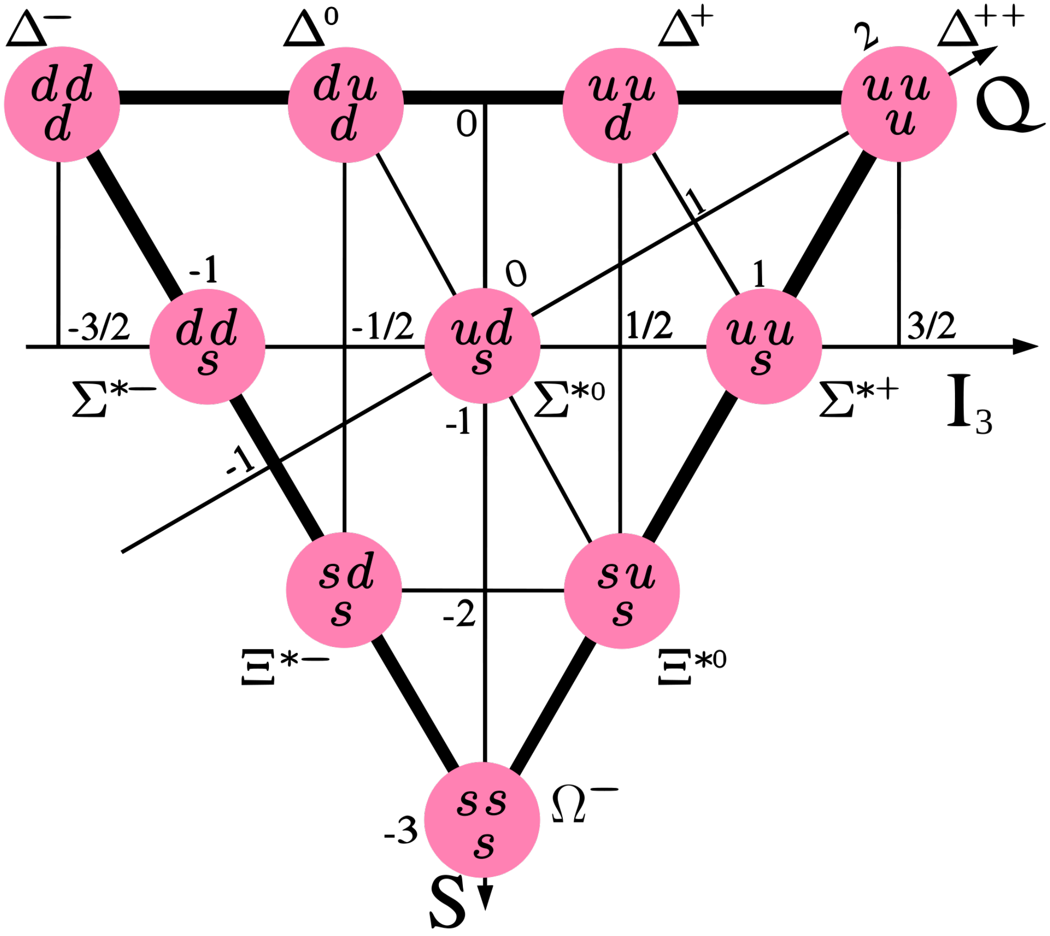
•*All states in a given grouping have the same orbital momentum of quarks with respect to each other. The "octet" in the previous slide corresponds to l = 0 single spin state. The spin of the meson is due to the arrangement of the spins of the quarks. Recall that antiquarks have opposite parity to quarks 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 spin =1/2 quarks (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:*

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

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

The baryon decuplet



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

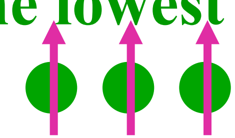
Prediction and discovery of the Ω^- particle

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)

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

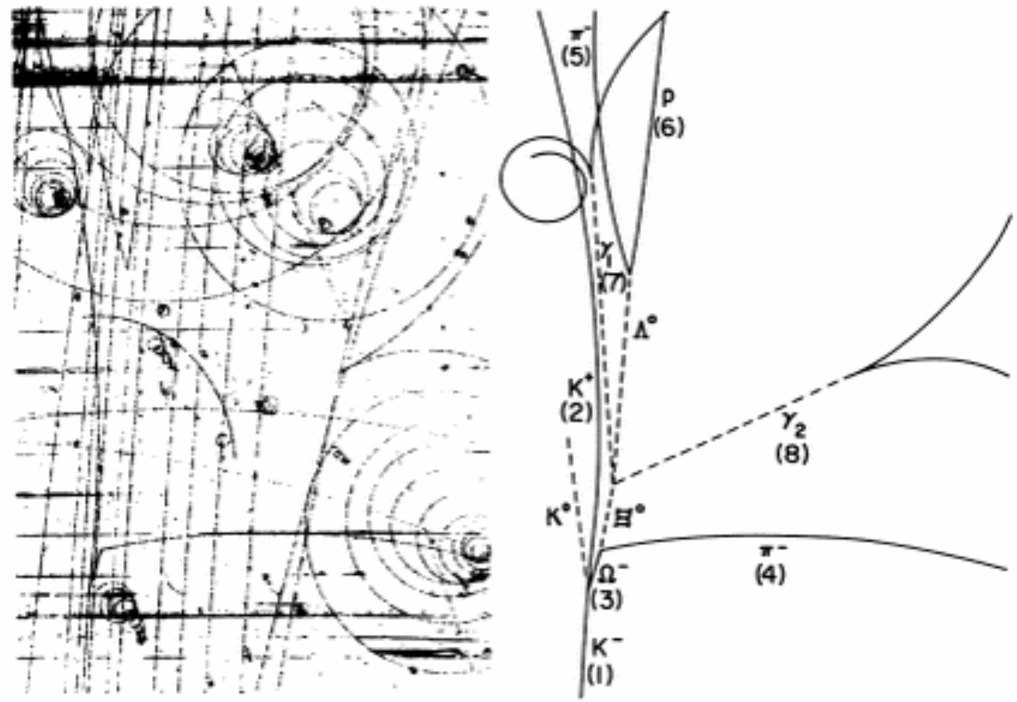
Chain of events in the picture:

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

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

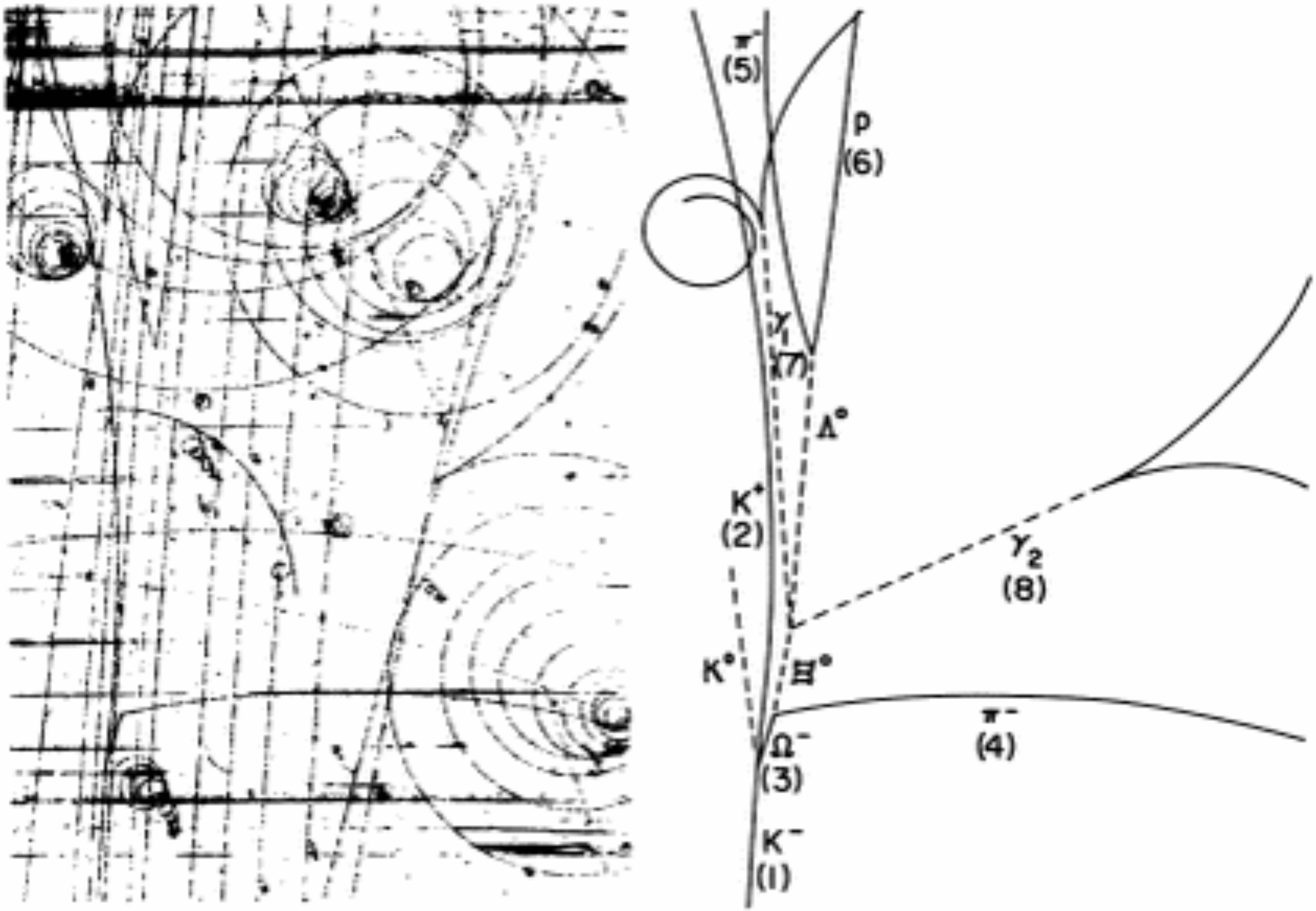
$\Xi° \rightarrow \pi° + \Lambda$ ($\Delta S = 1$ weak decay)

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



$\pi° \rightarrow \gamma + \gamma$ (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 over-constraint.

What followed was a long and unsuccessful 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.

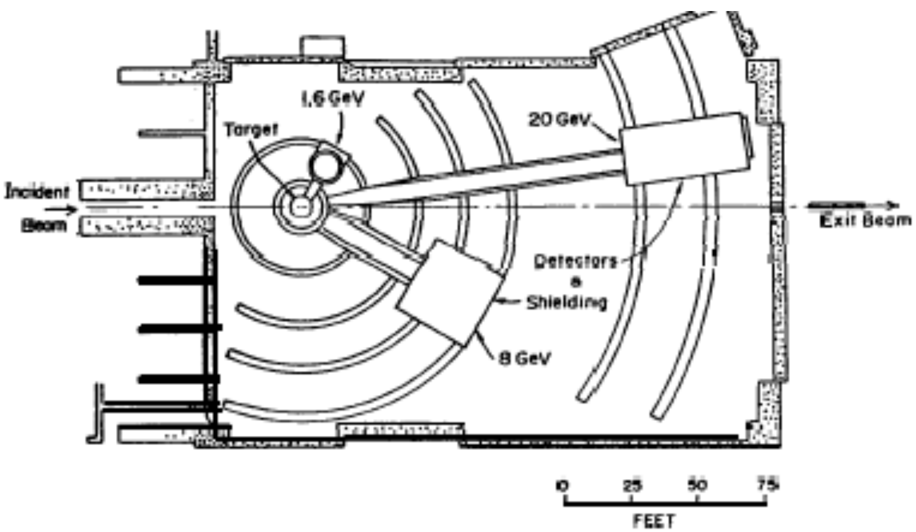
“DYNAMIC” EVIDENCE FOR QUARKS

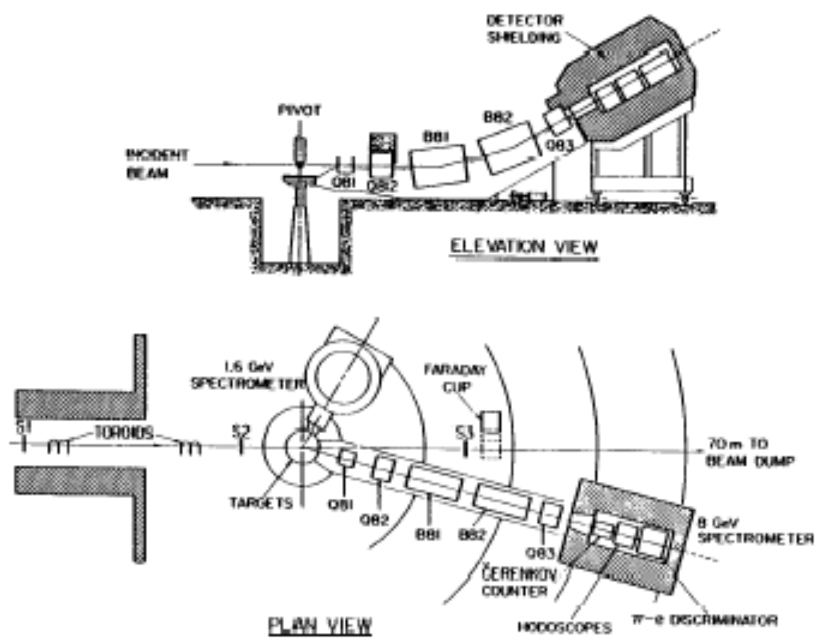
Electron – proton scattering using a 20 GeV electron beam from the Stanford two – mile Linear Accelerator.

The modern version of Rutherford's original experiment:
resolving power → wavelength associated with 20 GeV electron $\approx 10^{-15}$ cm

Three magnetic spectrometers to detect the scattered electron:

- **20 GeV spectrometer (to study elastic scattering $e^- + p \rightarrow e^- + p$)**
- **8 GeV spectrometer (to study inelastic scattering $e^- + p \rightarrow e^- +$ hadrons)**
- **1.6 GeV spectrometer (to study extremely inelastic collisions)**





The Stanford two-mile electron linear accelerator (SLAC)

Electron elastic scattering from a point-like charge $|e|$ at high energies: differential cross-section in the collision centre-of-mass (Mott's formula)

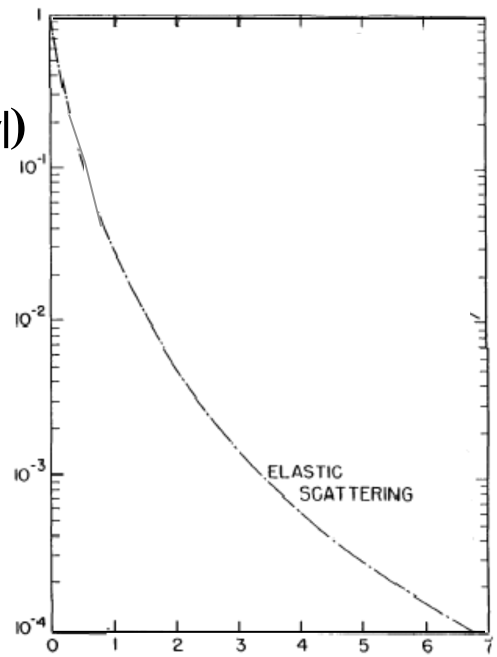
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 (\hbar c)^2}{8E^2} \frac{\cos^2(\theta/2)}{\sin^4(\theta/2)} \equiv \sigma_M \qquad \left(\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}\right)$$

Scattering from an extended charge distribution: multiply σ_M by a "form factor":

$$\frac{d\sigma}{d\Omega} = F\left(\left|Q^2\right|\right)\sigma_M$$

|Q| = ħ / D : mass of the exchanged virtual photon
D: linear size of target region contributing to scattering
Increasing |Q| −−> decreasing target electric charge

F(|Q²|)



|Q²| (GeV²)

$F(|Q^2|) = 1$ for a point-like particle
→ the proton is not a point-like particle

Kinematics of deep inelastic scattering