Emergence of zoo of hadrons—way too many to be elementary particles

- **Strange particles (late 1940s)**
- **Resonances (since early 1950s and on…)**

Proton has a size (direct measurement in 1956)—yet another evidence that hadrons may not be "elementary particles"

Sakata Model – precursor for the quark model

"Standard Model of late 1930s, early 1940s"

Simple beautiful picture:

Particles of matter	Particles of force	Odd piece
Proton	*photon*	*neutrino (not yet seen)*
Neutron	*meson (thought to be just discovered)*	
Electron		

Note that
- *neutron decays to proton+electron+neutrino:* $n \to p + e^- + \bar{\nu}$
- *mesons also decayed:* $meson^- \to e^- + \bar{?}$

1938 **Stückelberg** introduces new conservation law: conservation of *baryon* number[1]:
- *Baryon* number 1 for proton and neutron.
- Baryon number must be conserved at all times.

This would "explain" why protons/neutrons did not have the following decays, which otherwise are allowed by all known conservation laws (energy, momentum, angular momentum, charge):

$n \to meson^+ + e^- + \gamma$
$n \to meson^+ + e^-$
$n \to \nu + \gamma$
$p \to e^+ + \gamma$
$p \to \nu + meson^+$

Note that all these decays are also forbidden by the lepton conservation number, which was not yet introduced at that time

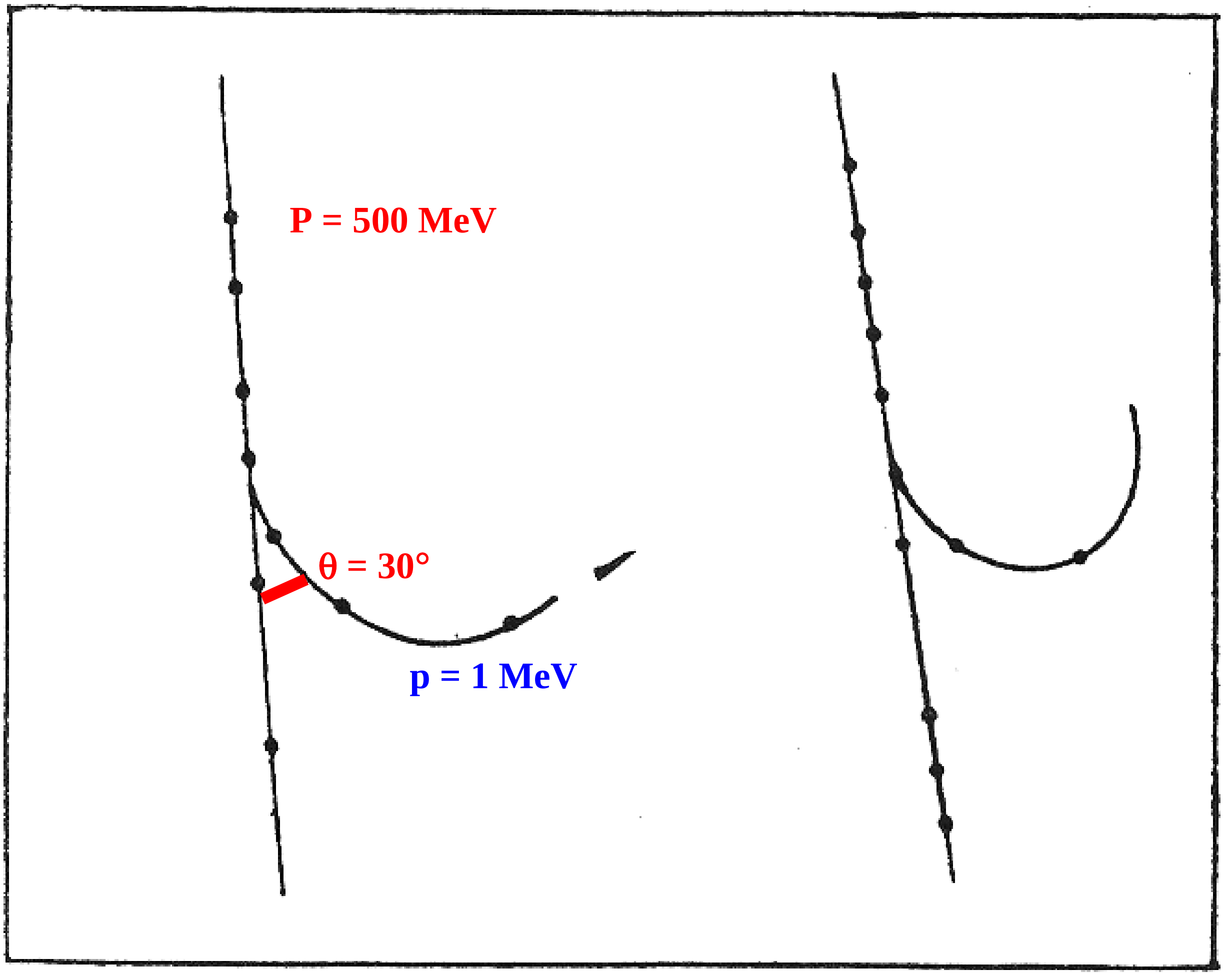
$n \to \bar{p} + e^+ + \nu$

This would not violate the lepton number conservation

[1] The name *baryon* ("heavy" in Greek) was coined later in 1953 by Pais

Strange Particles (late 1940s and early 1950s)

1943 **Leprince-Ringuet, L'heritier** First sighting of yet one more charged particle, heavier than the meson, but lighter than proton. Due to the war, this was published only 1946…
Cloud chamber 75×15×10 cm^3, 0.25 T, French Alps



Dessin stéréoscopique de la collision.

Kinematics of the event: incoming fast moving charged particle, kicks out an electron that was approximately at rest. From this, one can easily deduce the mass of the incoming particle:

Scattered electron: $p \approx 1$ MeV, $m = 0.5$ MeV, angle $\theta_0 \approx 30°$

Unknown particle: $P \approx 500$ MeV, scattering angle θ is very small, M is unknown

$$\sqrt{M^2 + P^2} + m = \sqrt{M^2 + P'^2} + \varepsilon$$
$$P = P'\cos\theta + p\cos\theta_0$$
$$0 = -P'\sin\theta + p\sin\theta_0$$

$$M = P\sqrt{\frac{\varepsilon + m}{\varepsilon - m}\cos^2\theta_0 - 1} \approx 506 \pm 61 \text{ MeV}$$

1947 **G. D. Rochester, C.C. Butler** (Manchester Group) observe in their cloud chamber:

$\theta^0 \rightarrow$ (positive) + (negative)
$\theta^+ \rightarrow$ (positive) + (neutral)

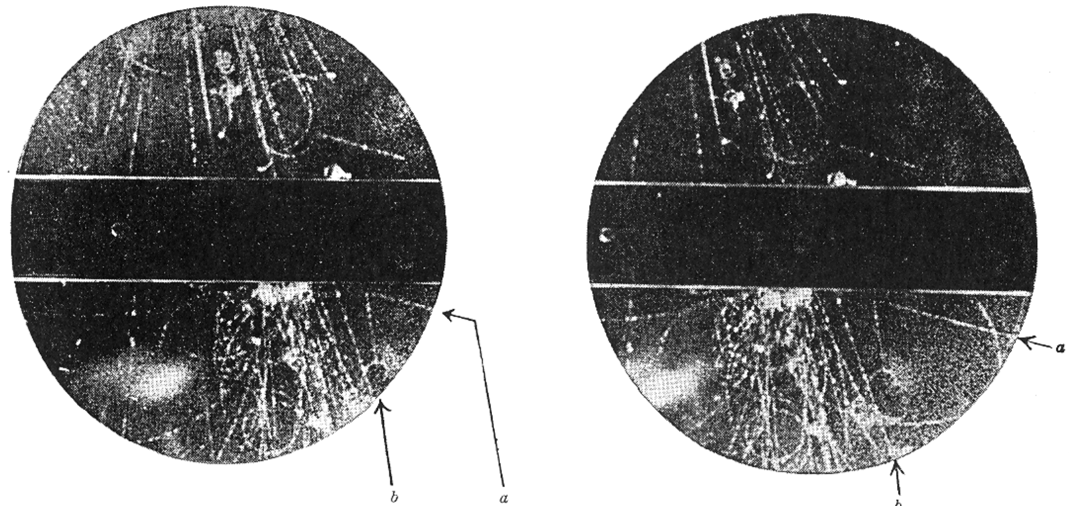


Fig. 1. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

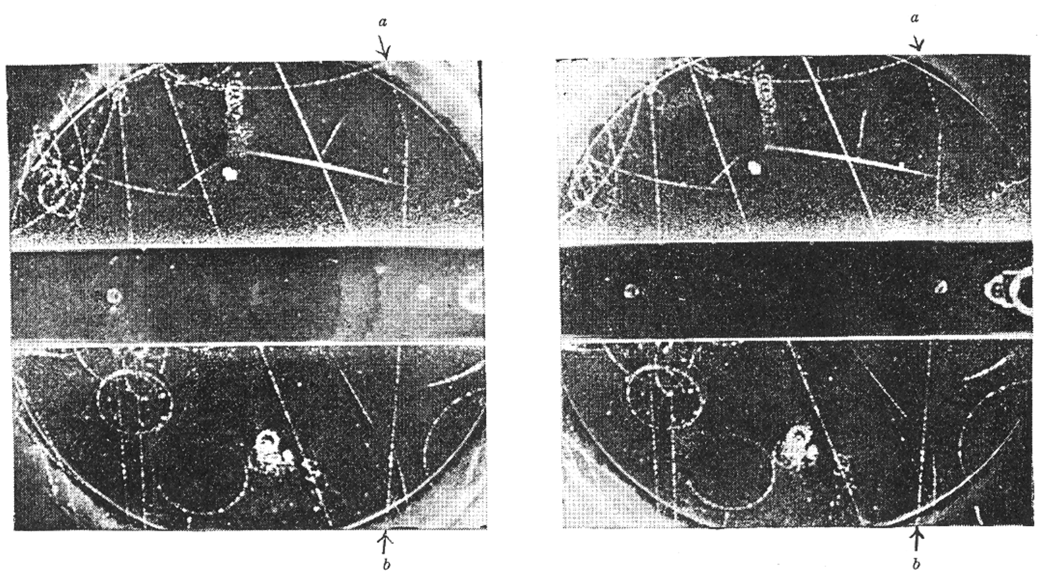


Fig. 2. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*). THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN A CLOCKWISE DIRECTION

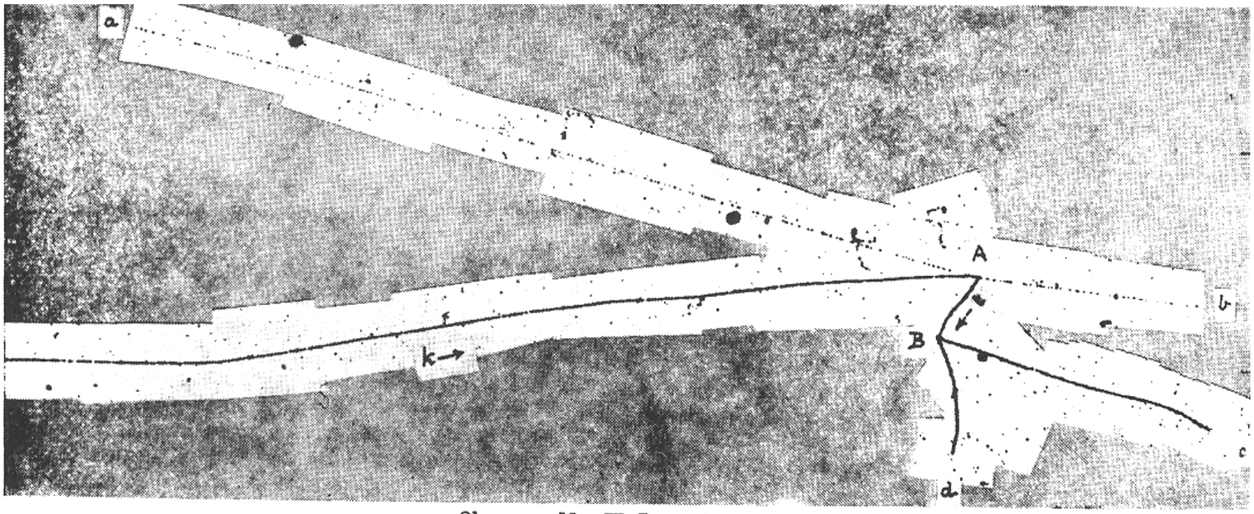
The masses of these particles were estimated to be about ~900±200 m_e (450±100 MeV), i.e., definitely higher than the mass of mesons (~200-300 m_e, note that by that time μ/π mystery was sorted out), but less than the mass of proton/neutron (~1900 m_e):

Assuming mass of (positive), (negative), (neutral) particles equals to:	Mass of θ^0	Mass of θ^+
0 m_e	770±200 m_e	980±150 m_e
200 m_e	870±200 m_e	1080±150 m_e
400 m_e	1110±150 m_e	1280±150 m_e

Decay time ~10^{-9}-10^{-10} s

1949 **C. F. Powell** (Bristol Group) reports a new heavy charged particle detected in the emulsion. It was created in a collision of a cosmic ray with nucleus and decayed into three charged particles, one which was slow and caused disintegration of nucleus in point B.

$\tau^+ \rightarrow$ (positive) + (positive) + (negative), all signs can be reversed
$M \approx 1000\ m_e$



Observer : Mrs. W. J. van der Merwe

Emulsion analysis technique:

- Density of grains ~$1/v^2$ for non-relativistic particles:
  → one can deduce that the particle was slowing down towards point of decay A
- Scale of scattering/wiggling (so called multiple Coulomb scattering) ~1/p
  → combined with grain density measurement, one can deduce particle's mass

1950 **Anderson** Group (Caltech) reports V-folk events similar to those seen by Rochester+Butler Group in Manchester. The pictures are taken with a cloud chamber as well.

$V^0_2 \rightarrow \pi^+ \pi^-$, mass not well determined
$V^0_1 \rightarrow p \ \pi^-$, must be quite heavier than proton! $\rightarrow$ **one more baryon?**

1951 **C. O'Ceallaigh** (Bristol Group, emulsions) reports a heavy particle decaying into (muon)+(neutrals):
$\kappa^{\pm} \rightarrow \mu^{\pm} + ?$
Particle's mass is 562±70 MeV.

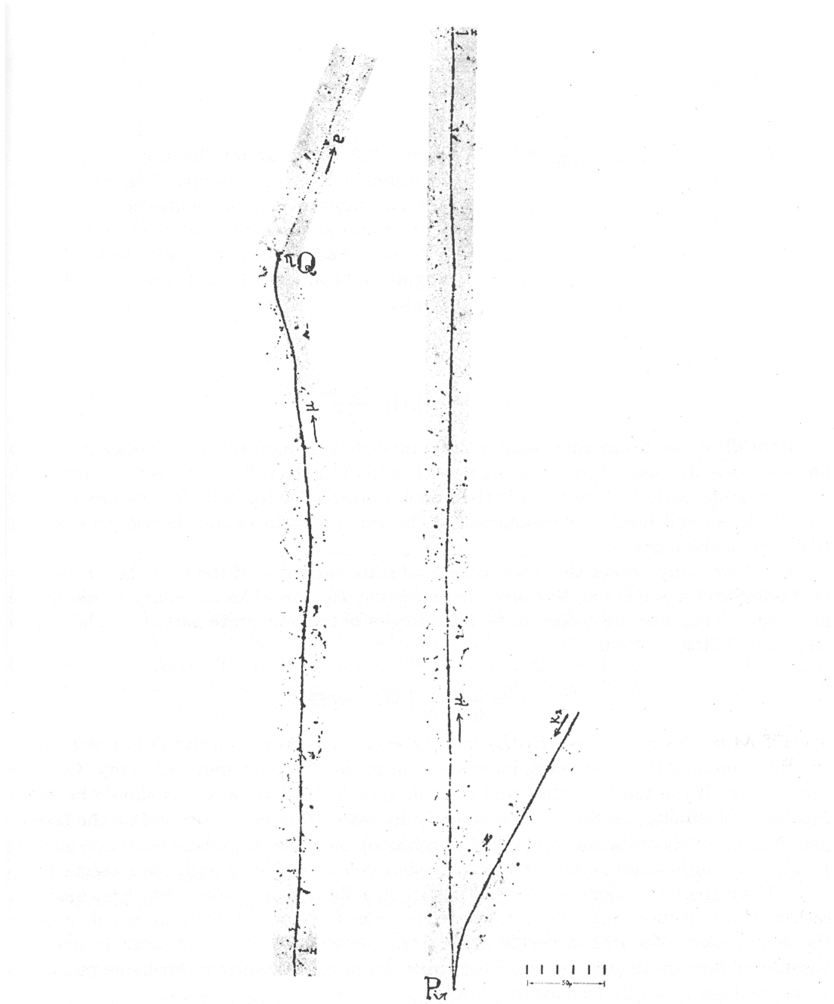


Figure 3.1: A κ (K) meson stops at P, decaying into a muon and neutrals. The muon decays at Q to an electron and neutrals. The muon track is shown in two long sections. Note the lighter ionization produced by the electron, contrasted with the heavy ionization produced by the muon near the end of its range. The mass of the κ was measured by scattering and grain density to be 562 ± 70 MeV (Ref. 3.4).

1953 **Thomson** Group (Indiana) reports a particle decaying into two well-measured charged pions:
$V^0_2 \rightarrow \pi^+ \pi^-$
Particle's mass = 2 m_π + 214±5 MeV = 494±5 MeV (today's value is 497 MeV)

1953 **Bonetti** (Bristol Group, emulsion) reports a heavy charged particle (baryon) decaying into (proton)+(neutrals):
$V^+_1 \rightarrow p + \text{(neutrals)}$

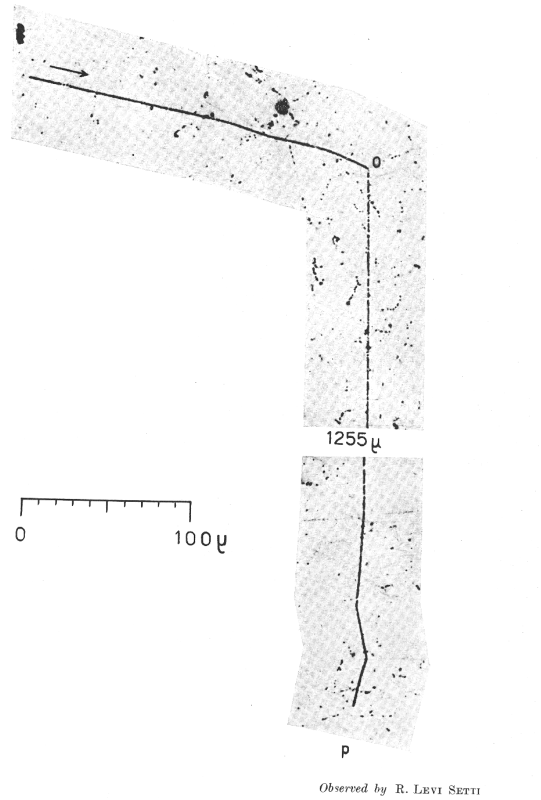
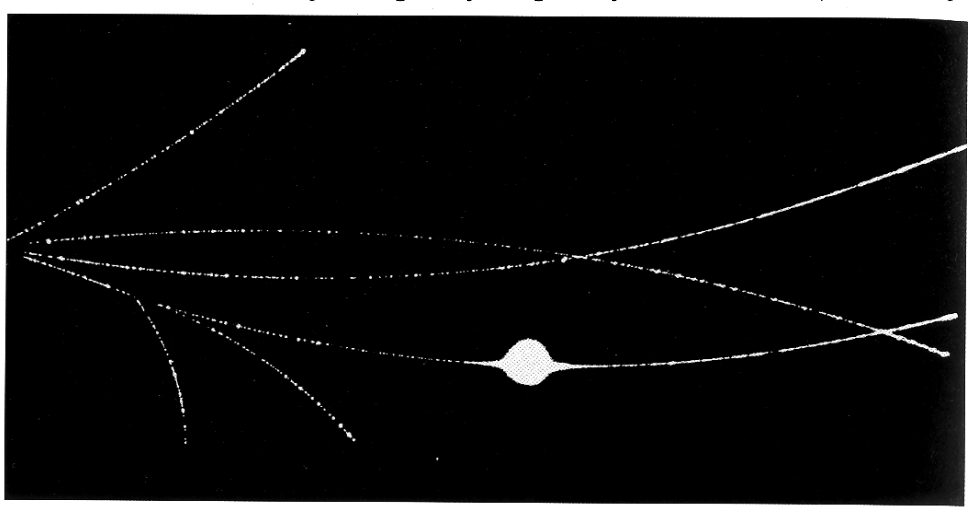


Figure 3.4: An emulsion event with a Σ^+ entering from the left. The decay is $\Sigma^+ \to p\pi$
The p is observed to stop after 1255 μm. (Ref. 3.8)

1953 **York** confirms seeing a similar event

1954 **Cowan** confirms V^+_1 and also reports negatively charged baryon $X^- \rightarrow V^0_1 + \pi^-$ (with $V^0_1 \rightarrow p + \pi^-$)



Bubble chambers: note the change in the quality of pictures—since 1952, the era of bubble chambers begins! This will be discussed a bit later in this lecture.
Cosmotron: Cosmotron, a 1.3 GeV proton accelerator, turns on in Brookhaven in 1952 (eventually, reached 3 GeV)
Bevatron: Bevatron, a 6.2 GeV proton accelerator, turns on in Berkeley in 1954

Summary (early 1950s):

1953 Conference at Bagneres-de-Biggorre, France

First seen in	Reported events	Current interpretation
	Mesons	
1943 (1946)	Charged particle with M~500 MeV	K^+
1947	$\theta^0 \rightarrow \pi^+ \pi^-$, $V^0_2 \rightarrow \pi^+ \pi^-$	$K^0 \rightarrow \pi^+ \pi^-$
1947	$\theta^+ \rightarrow \pi^+$ (neutral), $\chi^+ \rightarrow \pi^+$ (neutral)	$K^+ \rightarrow \pi^+ \pi^0$
1949	$\tau^+ \rightarrow \pi^+ \pi^+ \pi^-$	$K^+ \rightarrow \pi^+ \pi^+ \pi^-$
1951	$\kappa^+ \rightarrow \mu^+$ (neutrals)	$K^+ \rightarrow \mu^+ \nu$
	Baryons	
1950	$V^0_1 \rightarrow p\ \pi^-$	$\Lambda \rightarrow p\ \pi^-$
1953	$V^+_1 \rightarrow p$ (neutrals)	$\Sigma^+ \rightarrow p\, \pi^0$
?	$\Lambda^+ \rightarrow n\, \pi^+$	$\Sigma^+ \rightarrow n\, \pi^+$
(1953)	$X^- \rightarrow V^0_1\, \pi^-$	$\Xi^- \rightarrow \Lambda\, \pi^-$

Puzzle 1: **particles born in abundance → strong force**
decay into hadrons (strongly interacting particles),
but live for too long! ~10^{-10} s (consistent with Weak Force),
instead of ~10^{-23} s (time that would be typical for strong force)

This gave rise to the name *Strange Particles*

Puzzle 2: $\theta^+ \rightarrow \pi^+ \pi^0$ $J^P=0^-$
$\tau^+ \rightarrow \pi^+ \pi^+ \pi^-$ $J^P=0^+$
but have the same mass:

A) different particles with the same mass (~500 MeV) and spin (J=0)?
B) same particle, but parity P can be violated in its decays?

<u>We will discuss this puzzle later (the answer turned out to be B)</u>

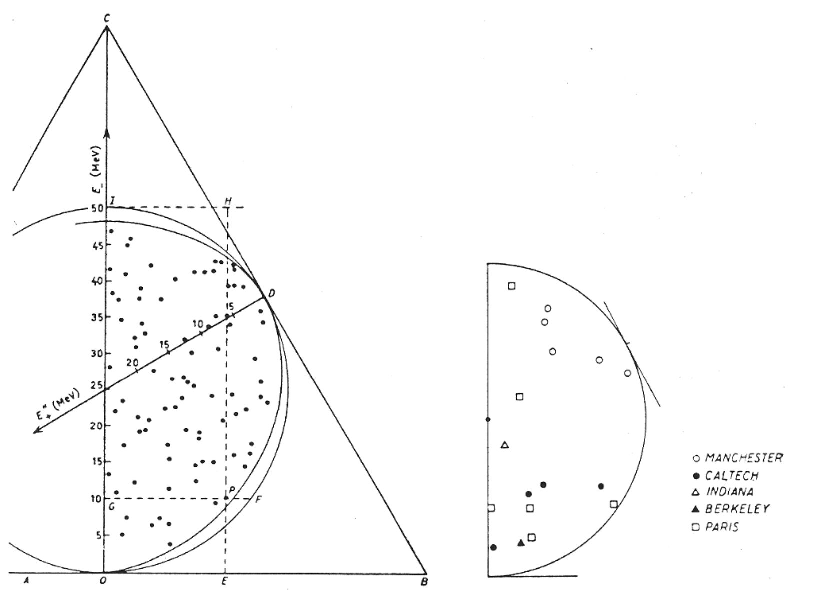
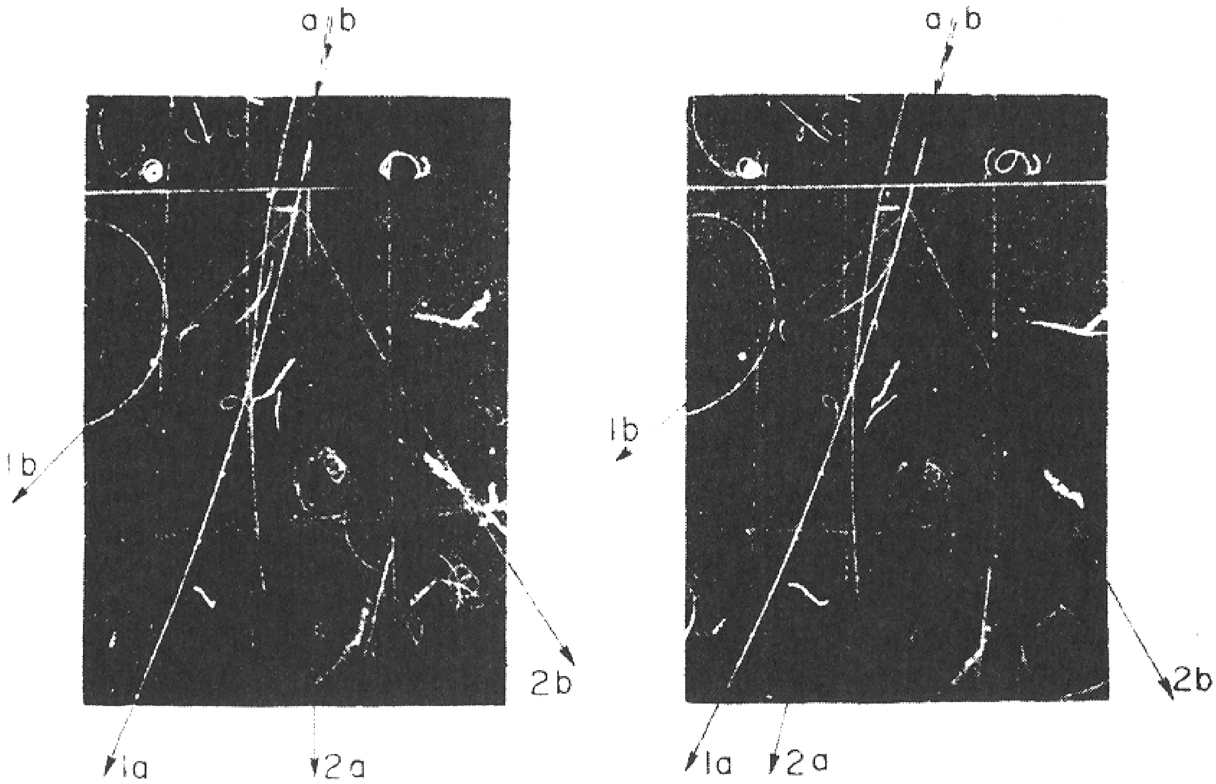


Figure 3.3: Dalitz plots showing worldwide compilations of tau meson decays ($\tau^+ \rightarrow \pi^+\pi^+\pi^-$) as reported by E. Amaldi at the Pisa Conference in June 1955 [*Nuovo Cimento Sup.* IV, 206 (1956)]. On the left, data taken in emulsions. On the right, data from cloud chambers. There is no noticeable depletion of events near $E_3 = 0$, *i.e.* near the bottom center of the plot. Parity conservation would thus require the tau to have $J^P = 0^-, 2^- \ldots$.

1952 **Pais** suggests that these new kind of particles can be produced in strong interactions, but only in pairs…

1953 **Fowler** indeed observes double V events obtained in the cloud chamber and 1.5 GeV π^- beam at the Cosmotron accelerator—first man-made strange particles!



1953 **Gell-Mann** and **Nishijima** independently suggested a new quantum number *Strangeness* (the term was coined by Gell-Mann) that would be conserved in strong and electromagnetic interaction, but not in weak

Q (electric charge, -1, 0, +1) – conserved always
L (lepton numbers, -1, 0, +1) – conserved always
B (baryon number, -1, 0, +1) – conserved always
S (strangeness, -1, 0, +1) – conserved in STRONG/EM, but no in WEAK interactions

→ severe opposition: if not always conserved, what kind of conservation law is that?
→ however, *Isospin* has been around already for a while; also, is not conserved in weak interactions:

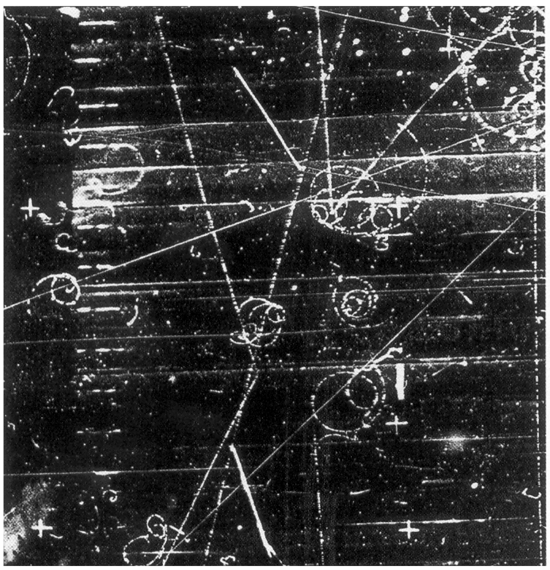
Isospin doublet (I=1/2): (n, p) $I_z = (-½, ½)$
Isospin triplet (I=1): (π^-, π^0, π^+) $I_z = (-1, 0, 1)$

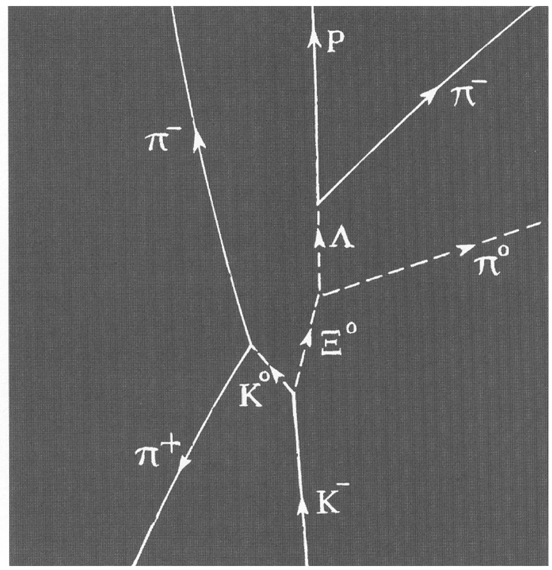
Gell-Mann-Nishijima formula: $\mathbf{Q = I_z + (B+S)/2}$
Decay of strange particles occurs via weak force and leads to $\Delta S=1$ and $\Delta I_z = 1/2$

Strangeness assignments

Mesons: S=0 for π^-, π^0, π^+ (isospin triplet)
S=+1 for K^0, K^+ (isospin doublet)
S=-1 for K^-, anti-K^0 (isospin doublet)

Baryons: S=0 for n, p (isospin doublet)
S=-1 for Λ (isospin singlet?)
S=-1 for Σ^-, $??^0$, Σ^+ (isospin triplet?, Λ is no good as it has a too different mass):
$\Sigma^0 \rightarrow \Lambda\gamma$ was discovered in 1955
S=-2 for $\Xi^- \rightarrow \Lambda\pi^-$ (S=-1, I_z =-1) ($\rightarrow I_z$ =-1/2: isospin doublet?):
$\Xi^0 \rightarrow \Lambda\pi^0$ was discovered in 1959





These assignments would allow for: and would not allow for:

	would allow for	would not allow for
$\pi^- p \rightarrow$	$K^0 \Lambda$	$K^0 \Lambda$
	$K^+ \Sigma^-$	$K^+ \Sigma^-$
	$K^0 \Sigma^0$	$K^0 \Sigma^0$
		$K^- \Sigma^+$

The following decays with ΔS=1 are allowed via weak force (resulting in long lifetimes):

$\Lambda \rightarrow p\ \pi^-$
$\Sigma^+ \rightarrow p\ \pi^0$
$\Sigma^+ \rightarrow n\ \pi^+$
$\Sigma^- \rightarrow n\ \pi^-$
$\Xi^- \rightarrow \Lambda\ \pi^-$

First Resonances (early 1950s):

1952 **Enrico Fermi** Group (Chicago University Cyclotron) reports seeing enhanced cross-sections (absorption) in process $\pi^+ p \rightarrow$ *anything*, which they suggest to interpret as a resonant stay of proton.

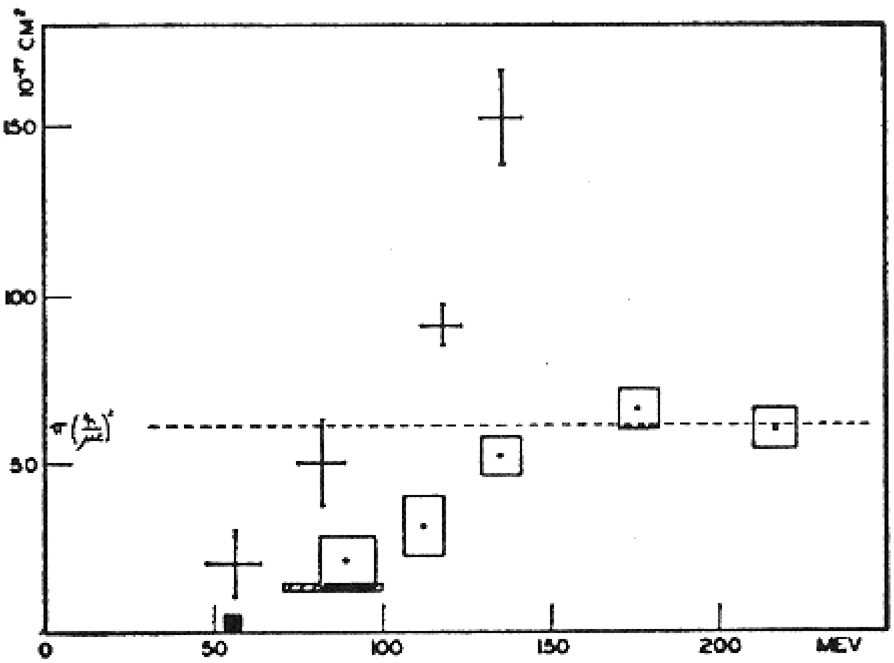
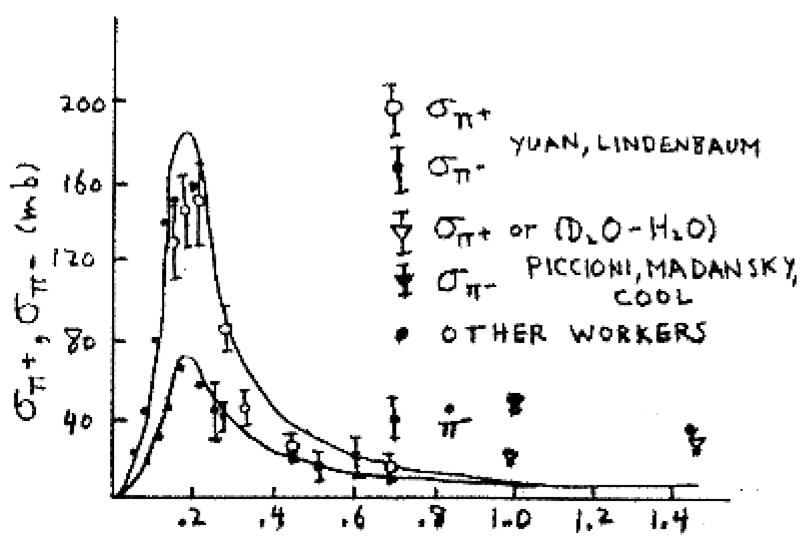


FIG. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

1954 **Yuon** from Brookhaven reports clear resonance curves for both

$\pi^+ p \rightarrow$ *anything*

$\pi^- p \rightarrow$ *anything*



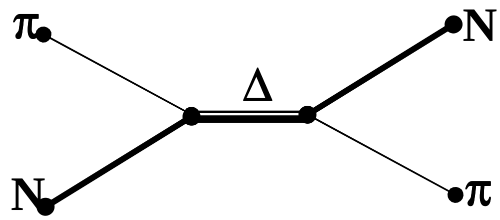
Δ-resonance

All of that can be explained via a process of creating a new very short lived particle Δ (proton resonance, proton excited state) with the mass M=1232 MeV, Γ=120 MeV ($\tau=1/\Gamma \sim 0.5\times10^{-23}$ s):

$$\sigma \sim \sigma_{\max} \frac{\Gamma^2/4}{(E-M)^2+\Gamma^2/4}$$

I_z (π^+ p) =3/2, so the particle must have I=3/2 or higher (it is 3/2), so there must be states with I_z=-3/2, -1/2, 1/2.

$\pi^+ p \rightarrow \Delta^{++} \rightarrow \pi^+ p$
$\pi^+ n \rightarrow \Delta^+ \rightarrow \pi^+ n$
$\pi^+ n \rightarrow \Delta^+ \rightarrow \pi^0 p$
$\pi^- p \rightarrow \Delta^0 \rightarrow \pi^0 n$
$\pi^- p \rightarrow \Delta^0 \rightarrow \pi^- p$
$\pi^- n \rightarrow \Delta^- \rightarrow \pi^- n$



Referring to the zoo of emerging strange and resonance-like particles:

Willis Lamb in his Nobel Prize speech in 1955 said: "… the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by $10,000 fine…"

More Nucleon Resonances

Invariant mass of πp system has many bumps!

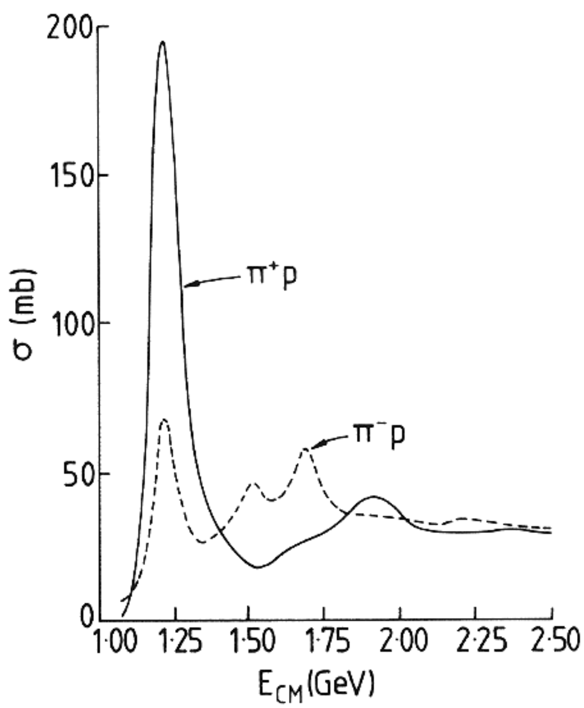
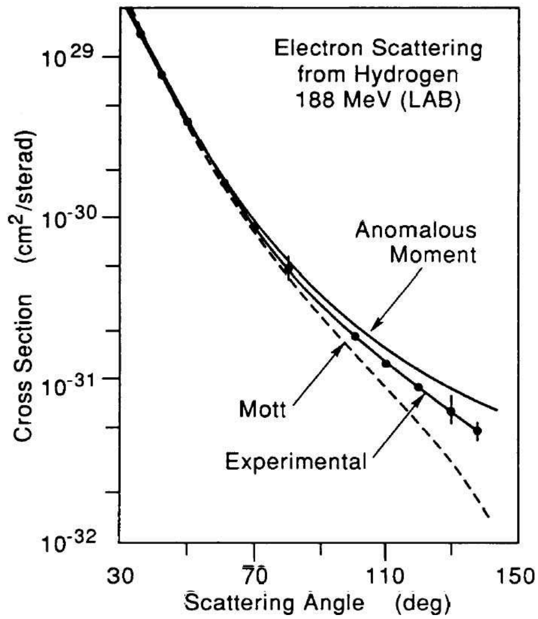


Fig. 5.6 Total cross-sections for $\pi^{\pm}$p scattering as a function of the total centre-of-mass energy E_{CM}.

Proton Structure

1956 **McAllister** and **Hofstadter** (Stanford linear accelerator Mark III) reported that scattering of electrons on protons deviated from the Rutherford formula (corrected for spin-1/2, Mott formula, and further corrected for proton's anomalous magnetic moment). This could be interpreted as if proton's charge was distributed over 0.7±0.2 fm distances…



Even more resonances

Strange baryons:

1960 **Alvarez** Group (bubble chamber at Bevatron, Berkeley):

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

invariant mass of the $\Lambda\pi$-system: Σ^{+*} and Σ^{-*} resonances with M~1380 MeV

NOTE: a new technique of reconstructing resonances by searching for peaks in the invariant mass of decay products

Strange mesons:

1961 **Alvarez** Group (bubble chamber at Bevatron, Berkeley):

$K^- p \rightarrow \bar{K}^0 \pi^- p$

invariant mass of the $\bar{K}^0\pi^-$-system: K^{-*} resonance with M~880 MeV

Non-strange mesons:

1961 **Ervin et al.** (bubble chamber at Cosmotron, Brookhaven):

$\pi^- p \rightarrow \pi^- \pi^0 p$

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

invariant mass of the $\pi\pi$-system: ρ^- and ρ^-resonance with M~770 MeV

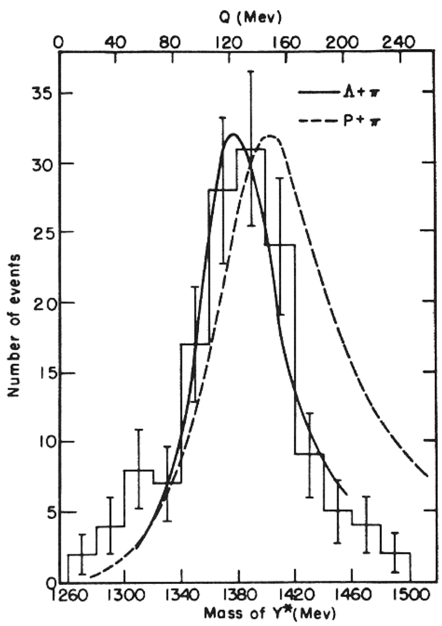
Three-particle resonances:

1961 **Alvarez** Group (bubble chamber at Bevatron, Berkeley):

$\bar{p}\, p \rightarrow 2\pi^+ 2\pi^- \pi^0$

invariant mass of the $\pi^+\pi^-\pi^0$-system: ω-resonance with M~790 MeV (fairly long lived τ~7×10^{-23} s)

1968 **Alvarez** is awarded Nobel Prize *"for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using hydrogen bubble chamber and data analysis"*



Σ* resonance (Λπ)

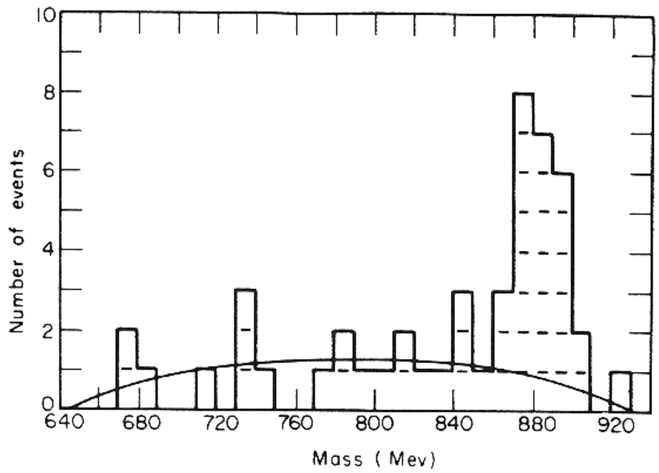
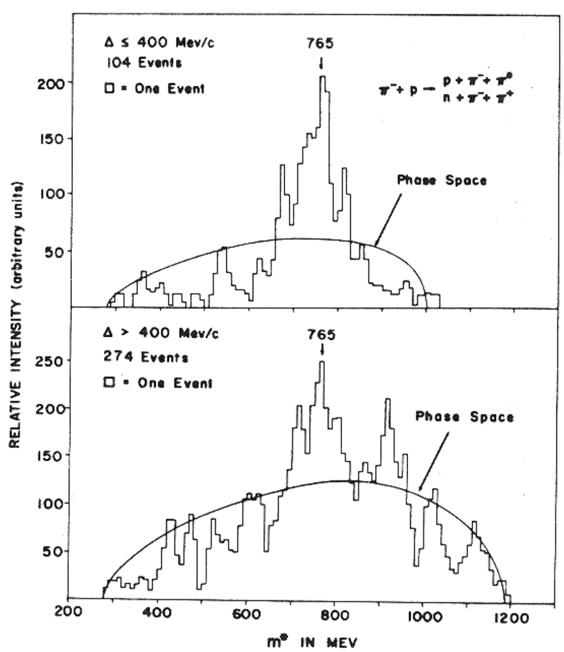
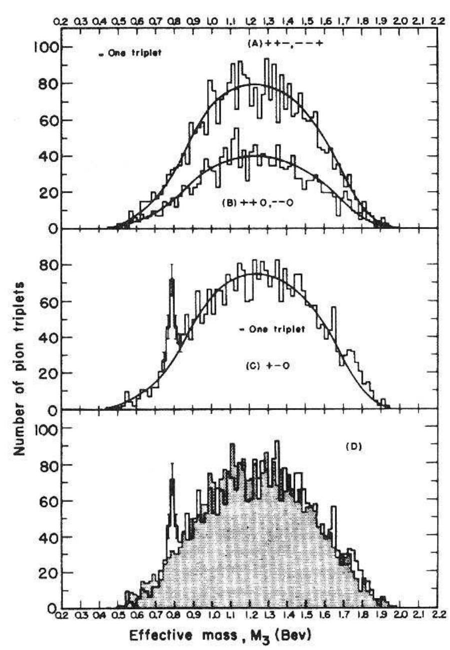


FIG. 2. Mass spectrum of the $\bar{K}^0 - \pi^-$ system. The solid line represents the phase-space curve normalized to background events.

K* resonance (Kπ)



ρ resonance (ππ)



ω resonance ($\pi^+\pi^-\pi^0$)

Sakata Model

1956 **Sakata** extended the Fermi-Yang idea of treating pions as nucleon-antinucleon bound states, e.g. $\pi^+ = (p\ \bar{n})$

All mesons, baryons and their resonances are made of p, n, Λ and their antiparticles:

Mesons (B=0):

	p	n	Λ
$\bar{p}$	?	π^-	K^-
$\bar{n}$	π^+	?	$\bar{K}^0$
$\bar{\Lambda}$	K^+	K^0	?

Note that there are three diagonal states, $\bar{p}p$, $\bar{n}n$, $\bar{\Lambda}\Lambda$.
Therefore, there should be 3 independent states, three neutral mesons:
$\pi^0 = (\bar{p}p - \bar{n}n) / \sqrt{2}$ with isospin I=1
$X^0 = (\bar{p}p + \bar{n}n) / \sqrt{2}$ with isospin I=0
$Y^0 = \bar{\Lambda}\Lambda$ with isospin I=0
Or the last two can be mixed again…
(Actually, later discovered η and η' resonances could be interpreted as such mixture)

Baryons (B=1):

S=-1 $\Sigma^+ = (\Lambda\ p\ \bar{n})$
$\Sigma^0 = (\Lambda\ n\ \bar{n})$ mixed with $(\Lambda\ p\ \bar{p})$ → what is the orthogonal mixture?
$\Sigma^- = (\Lambda\ n\ \bar{p})$

S=-2 $\Xi^- = (\Lambda\ \Lambda\ \bar{p})$
$\Xi^0 = (\Lambda\ \Lambda\ \bar{n})$

S=-3 NOT possible

Resonances (B=1):

$\Delta^{++} = (p\ p\ \bar{n})$
$\Delta^+ = (p\ n\ \bar{n})$ mixed with $(p\ p\ \bar{p})$ → what is the orthogonal mixture?
$\Delta^0 = (n\ n\ \bar{n})$ mixed with $(n\ p\ \bar{p})$ → what is the orthogonal mixture?
$\Delta^- = (n\ n\ \bar{p})$

Sakata Model was the first attempt to come up with some plausible internal structure that would allow systemizing the emerging zoo of hadrons. Retrospectively, it was a precursor of the Quark Model to be discussed in the next lecture. However, the model was giving completely wrong magnetic moments and not allowed for a baryon with S=-3. The latter was in dramatic difference with the Eightfold Way, a systematization of particles based on the SU(3) symmetry.

Bootstrap Model was entertained by some theorists in 1950-1960s (especially G. Chew). The idea was that hadrons were made of the very same hadrons and one would not need to introduce new constituents, e.g. p, n, and Λ would be the missing orthogonal mixtures of p, n, Λ, and their antiparticles. If it worked, the quest for smaller and smaller constituents of matter would be over. The theory got its name after one of Baron Münchausen's stories: *"the only way out of swamp was to pull yourself up by your own bootstraps"*