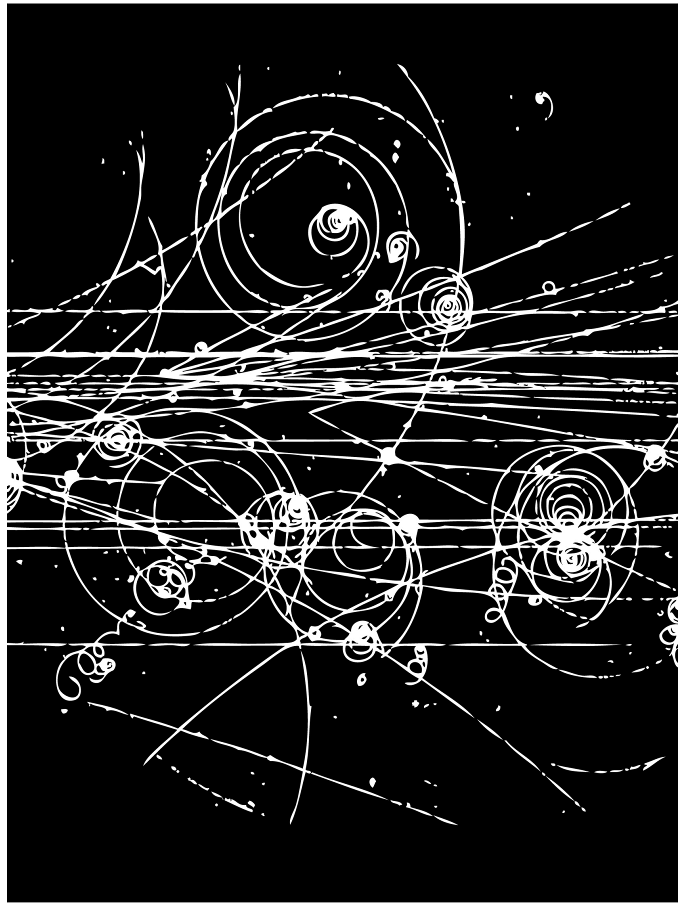
Hadron Spectroscopy



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Institute for Basic Science (KOREA)
University of the Chinese Academy of Science

UCAS Physics-department, June 20 – July 6, 2014

Summary (lecture 1)

- The (expected) discovery of the π-meson and the (unexpected) discovery of the K-meson & Λ baryon in 1947 marked the beginning of hadron physics.

- The fact that K-mesons were produced in association with Λ-baryons led to the discovery of Strangeness, the 1st flavor. S is conserved in strong and electro-magnetic, but not in weak interactions.

- Experiments showed that the spin and parity of the π, K and η mesons are all $J^P=0^-$.

- A matching set of meson resonances with $J^P=1^-$, the ρ, K* and ω mesons, were found in bubble chamber experiments.

- A set of spin=3/2 baryon resonances, the Δ(1232), Y*(1385) (now called the Σ(1385)) and Ξ(1530) was also discovered.

- Mesons come in octets; baryons come in octets and decuplets.

Lecture 2: Are hadrons made from more fundamental constituents?

But 1st: Why are Ξ baryons called "cascades?"

Ξ 🡐 Greek letter"Xi"

"cascade" 🡐English word for multi-tier waterfall

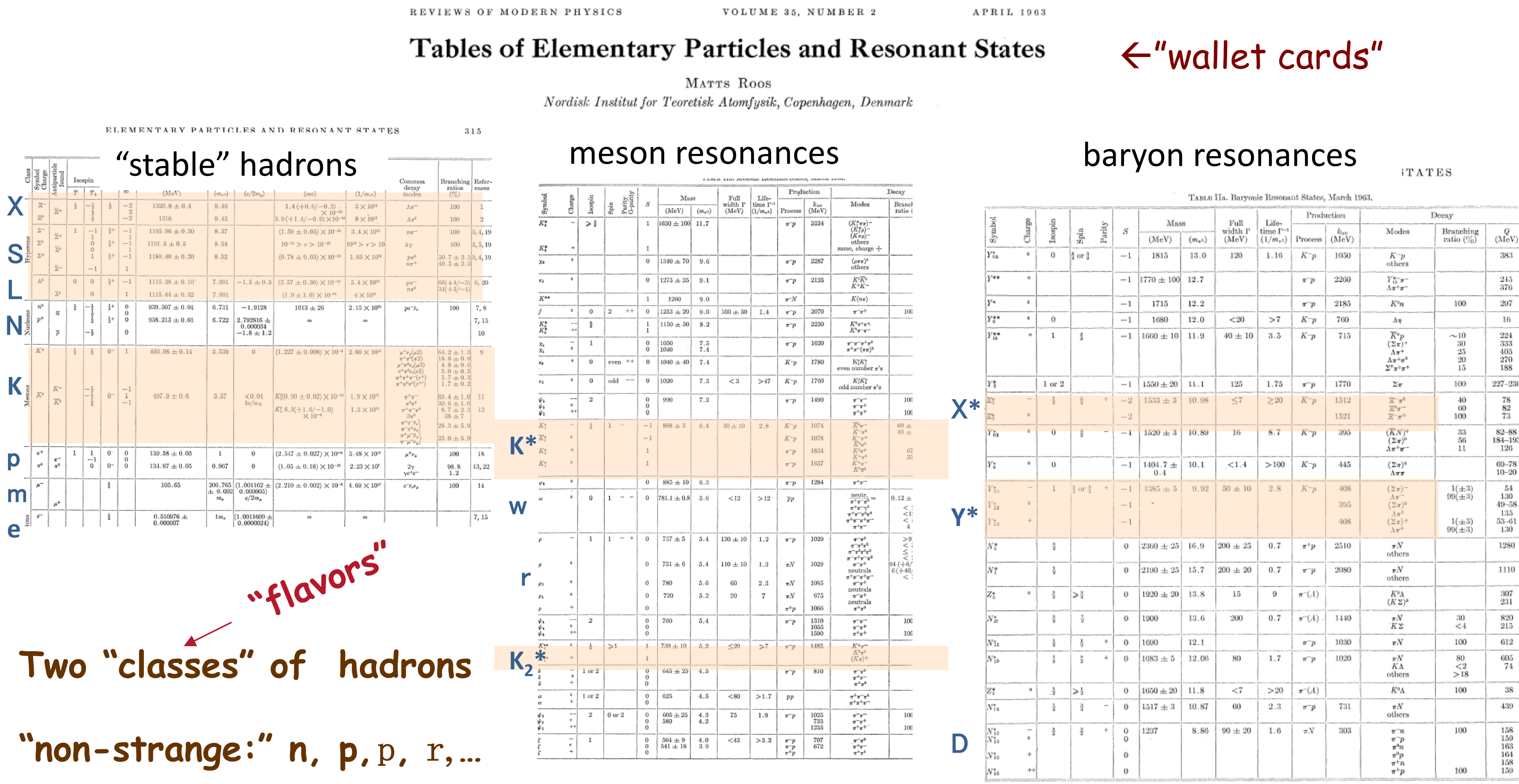
Cascade Waterfall

$$K^- p \rightarrow K^0 \Xi^0 \pi^+ \pi^-$$

$$K^0 \rightarrow \pi^+\pi^- \qquad \Xi^0 \rightarrow \pi^0 \Lambda^0$$

$$\pi^0 \rightarrow \gamma\, e^+ e^- \qquad \Lambda^0 \rightarrow \pi^- p$$

Elementary particle "Zoo" in 1963



Two "classes" of hadrons

"non-strange:" n, p, π, ρ, ...

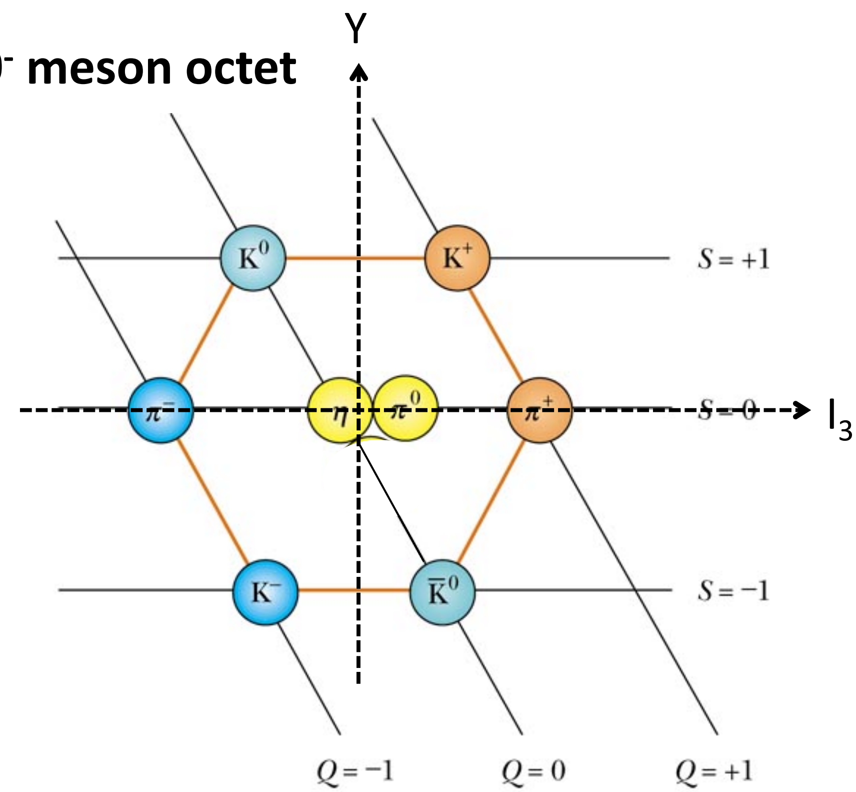
"strange:" Λ, Σ, K, K*, ...

Meson and Baryon Octets

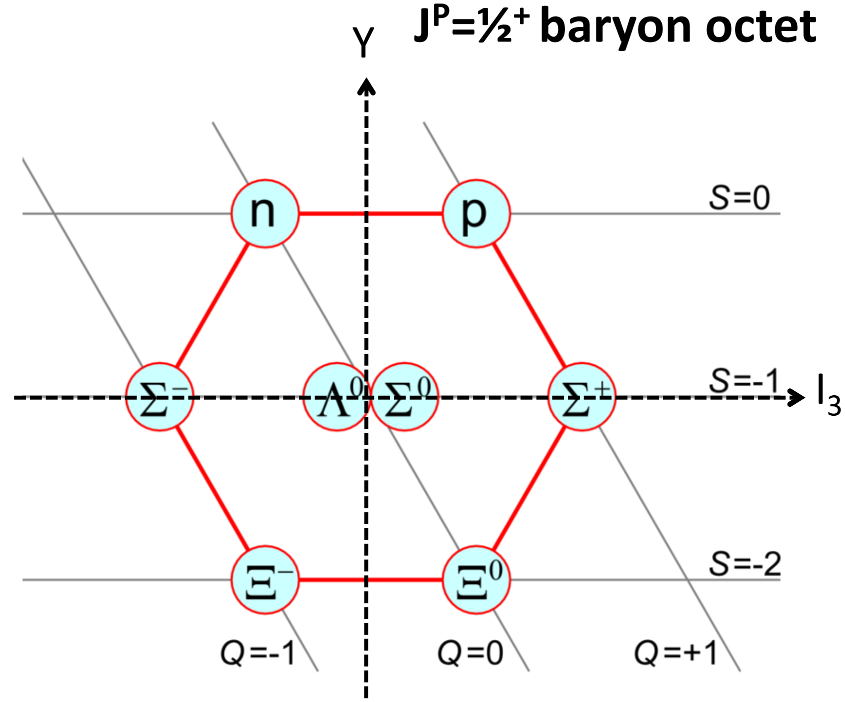
strangeness → S; baryon number → B

Y = "hypercharge" = S+B; I_3= 3rd I-spin component

$J^P=0^-$ meson octet

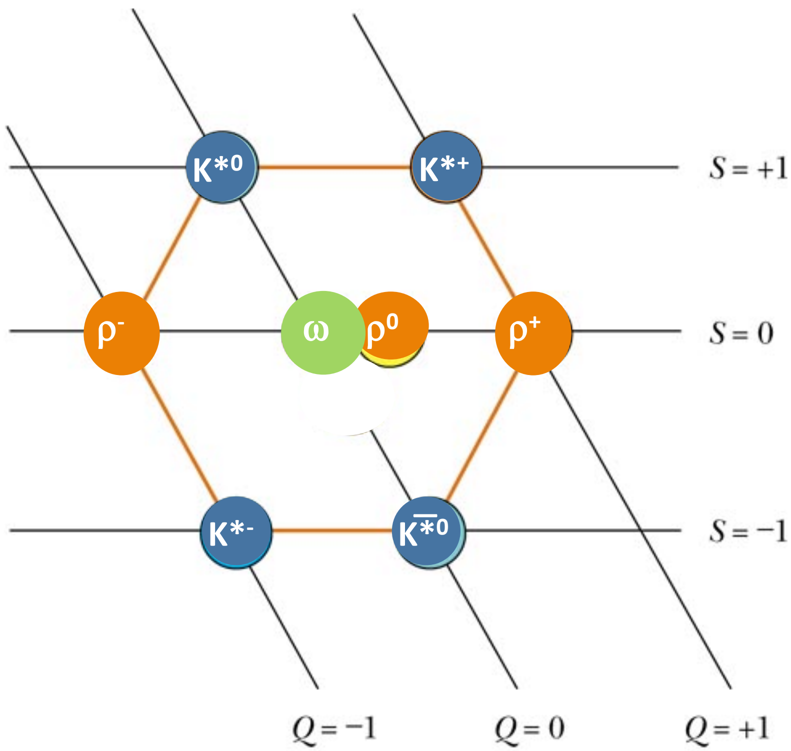


$J^P=½^+$ baryon octet

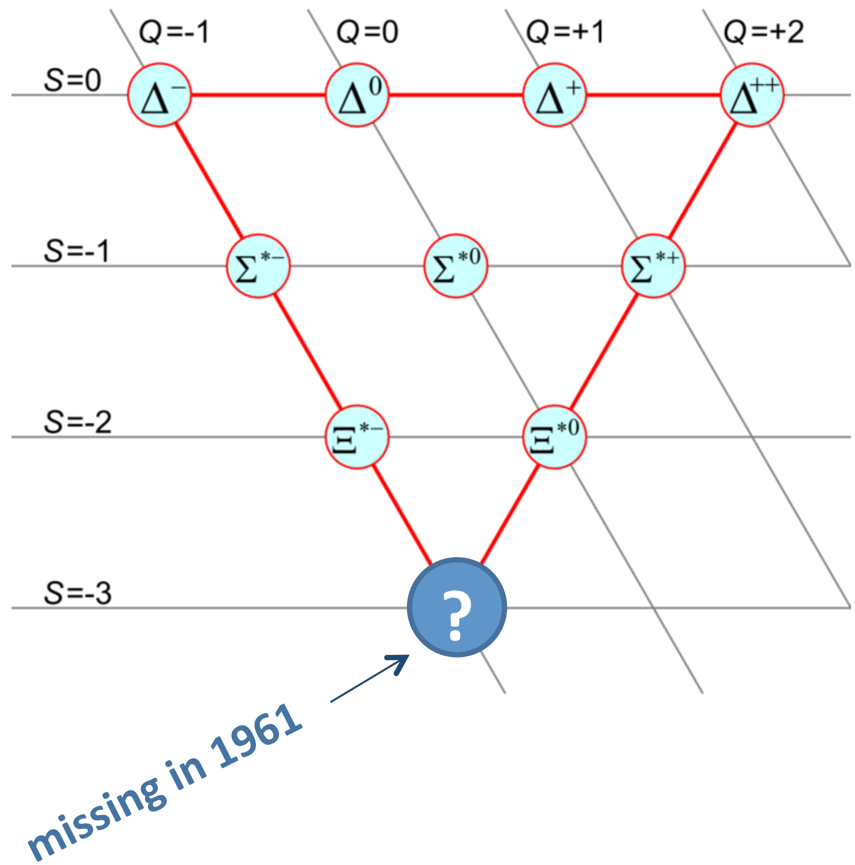


resonances

$J^P=1^-$ vector meson octet



$J^P=3/2^+$ baryon "decuplet"



1^{st} attempts at Classification

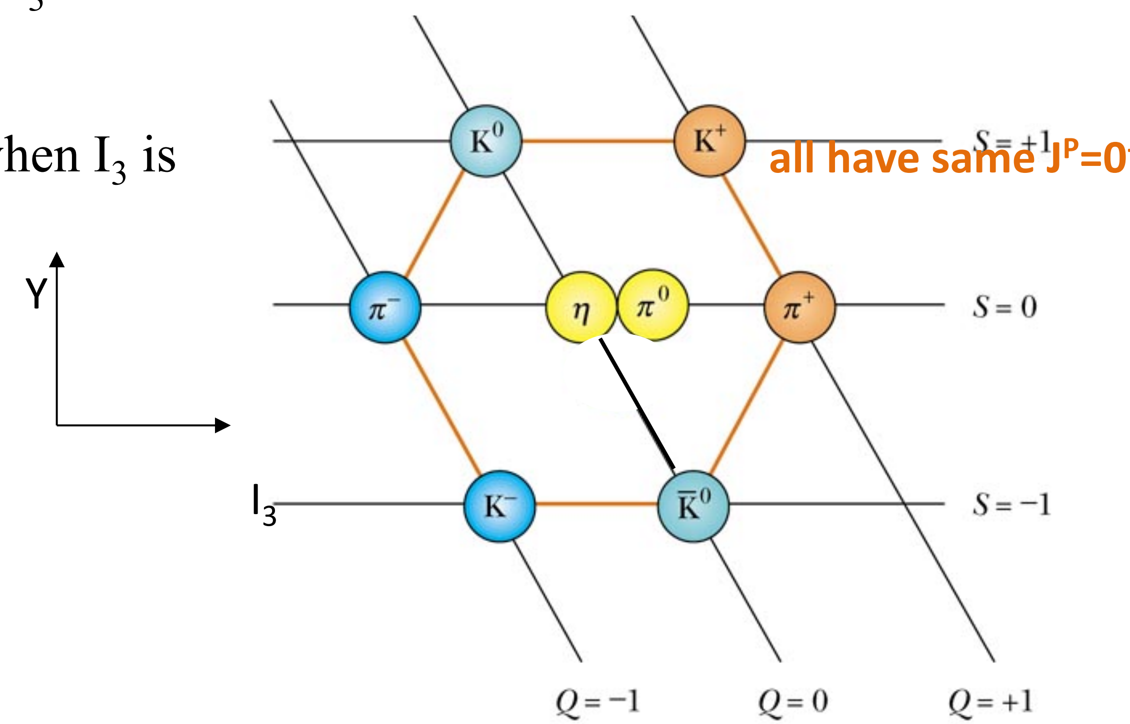
Gell-Mann, Nakano, Nishijima realized that electric charge (Q) of all particles could be related to isospin (3rd component), Baryon number (B) and Strangeness (S):

$$Q = I_3 + (S + B)/2 = I_3 + Y/2$$

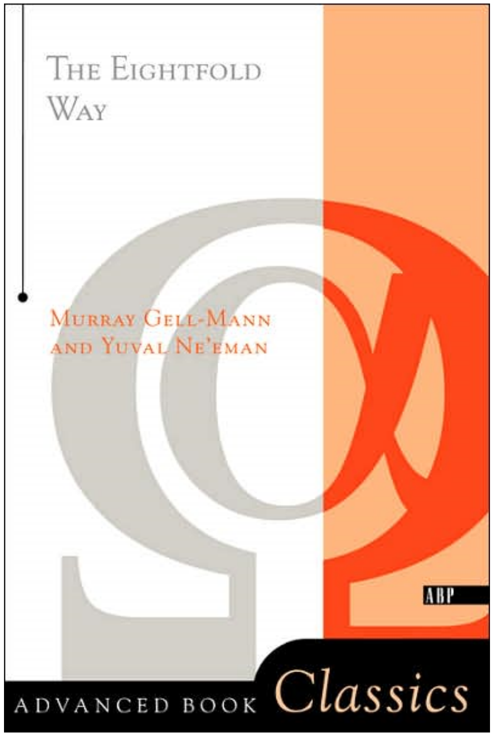
hypercharge **(Y) = (S+B)**

Interesting patterns emerge when I_3 is plotted vs. Y

Meson "octet"



1961: Gell-Mann, Nishijima & Nee'man: The Eightfold Way



The Eightfold Way appears in the Buddhist teaching: "This is the noble truth that leads to the cessation of pain. This is the noble eightfold way. . ."

Octets (and decuplets) are representations of the SU(3) Lie group:

SU(2) group:
Angular Momentum in QM

Pauli Matrices

$$\sigma_1 = \sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_2 = \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\sigma_3 = \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

Representations:

$$\begin{pmatrix} +\frac{1}{2} \\ 0 \end{pmatrix} \begin{pmatrix} 0 \\ -\frac{1}{2} \end{pmatrix}$$

Spin=1/2

$$\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad \ldots$$

Spin=1

SU(3) group:
Generalization of SU(2)

Gell-Mann Matrices

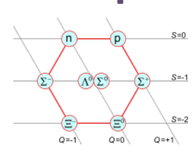
$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$$

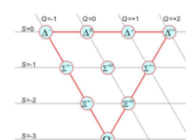
$$\lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \qquad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Representations:


octets

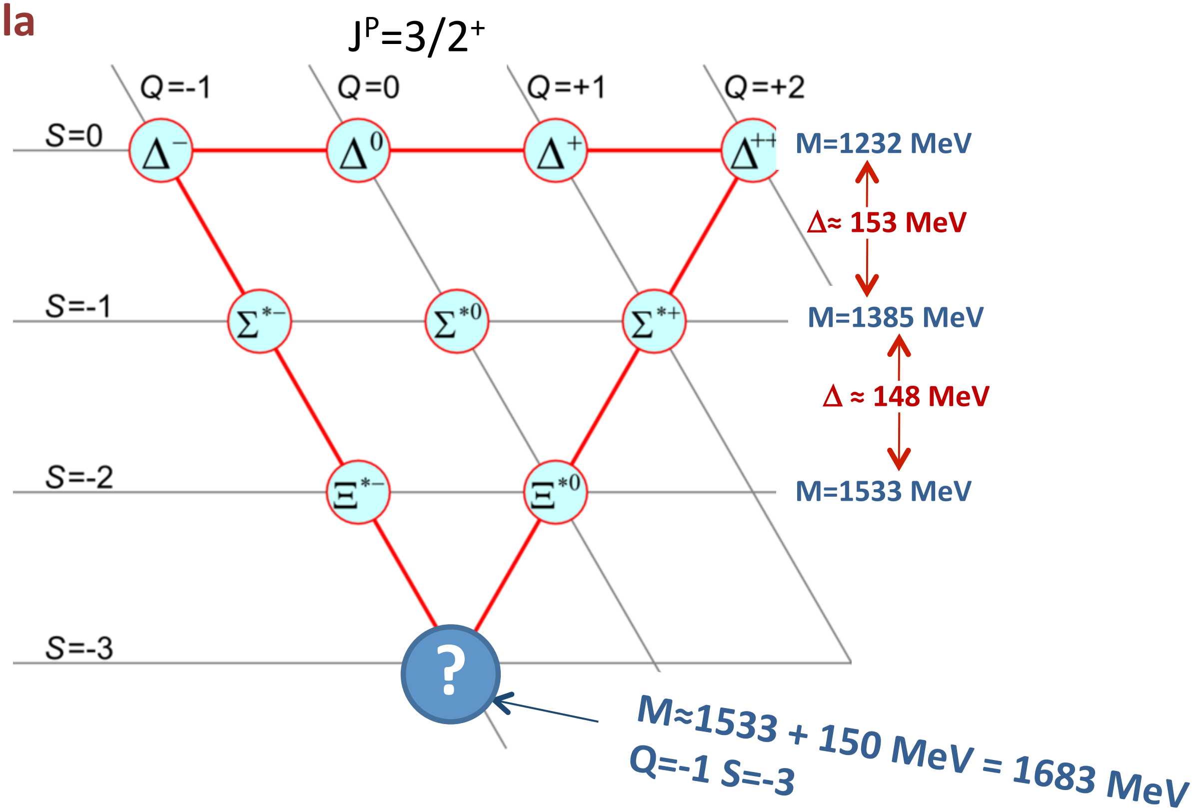

decuplets

…

SU(3) prediction for the Ω^- mass

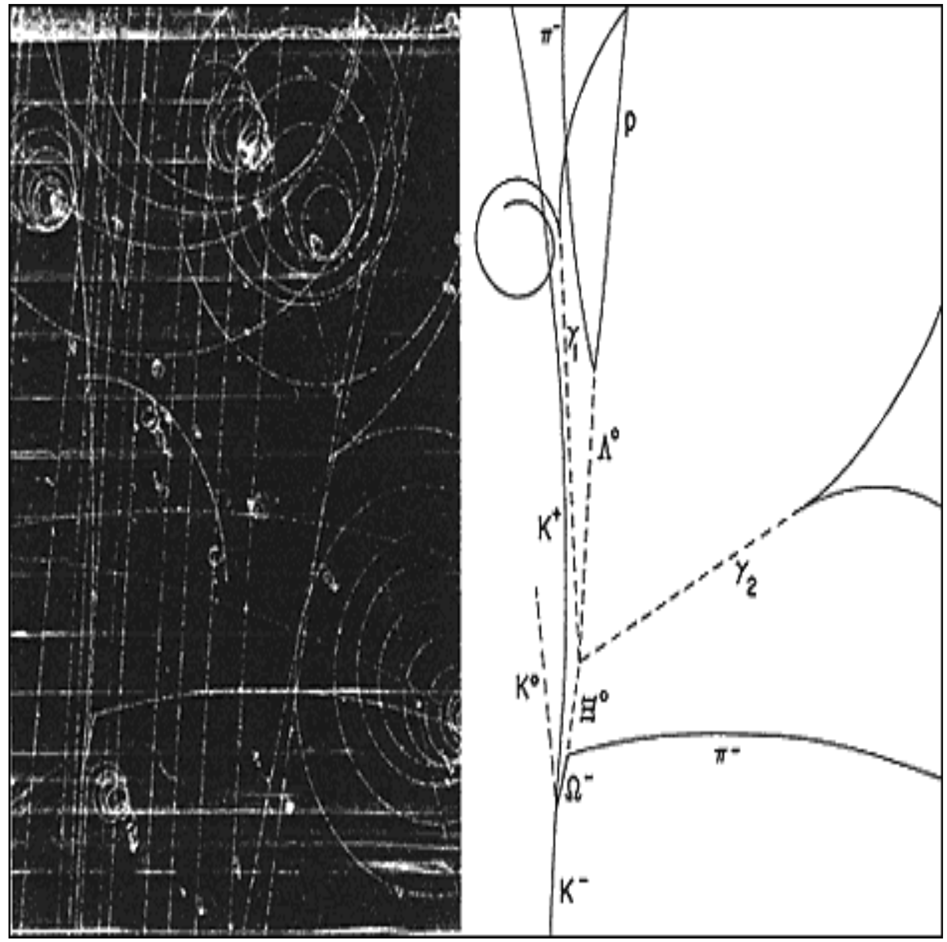
Gell-Mann Okubo mass formula

Each unit of Strangeness increases M by 150 MeV

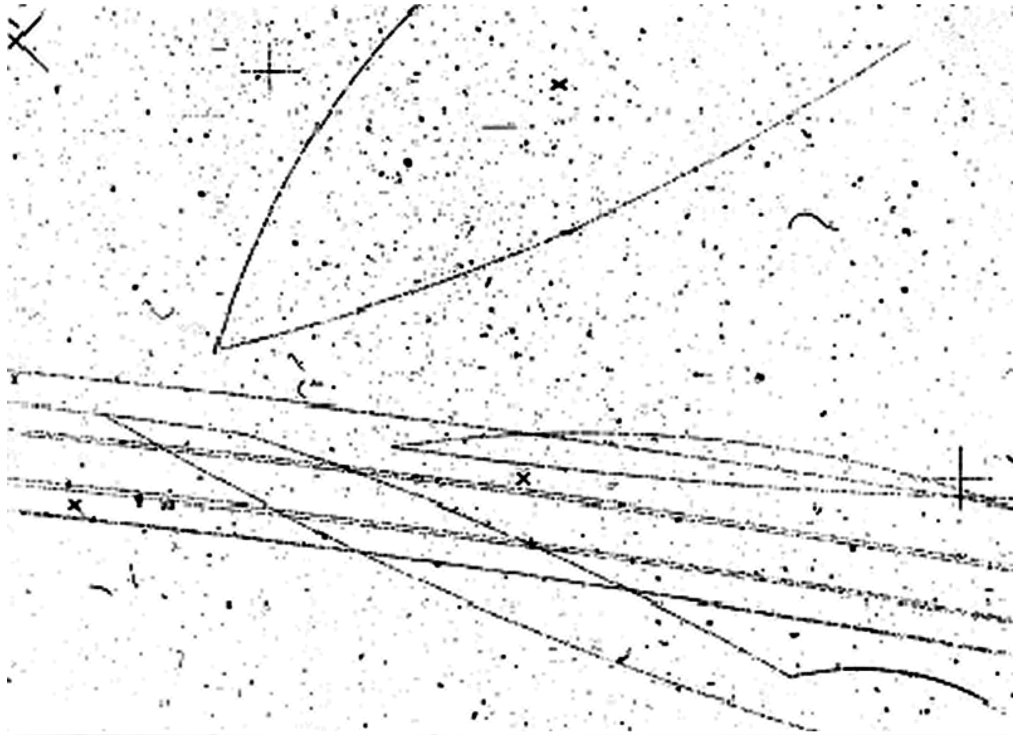


1965: Ω^- discovery

1965: the Ω^- was discovered at the Brookhaven Lab in NY. USA with S=-3 & M = 1672 MeV, near the Gell-Mann/Okubo prediction



Ω^- seen at CERN too



Omega minus produced by 4.2GeV K^-

This remarkable event shows the production and decay of an omega-minus by a 4.2 GeV beam K^- particle in the CERN 2 metre hydrogen bubble chamber.

In this event there are two vees: one comes from the primary interaction while the other comes from the kink. (You can check this by printing off the event and then following back - with a ruler - the line joining the point where the vee tracks cross to the vee decay point. It clearly points to the kink.)

The track from the kink must be a K^- or a π^-, depending on whether the parent particle was an Ω^- or a Ξ^-. This track itself kinks, quite considerably, telling us that it is a K^-. (The mass of a μ is so close to that of a π that it could not provide the energy to produce such a sharp kink.)

So, without any measurements, we have identified an Ω^- decaying to $\Lambda^0 K^-$.

A measurement of the event reveals that the reaction is

$$K^- p \rightarrow \Omega^- K^+ K^0$$
$$K^0 \rightarrow \pi^+ \pi^-$$
$$\Omega^- \rightarrow \Lambda^0 K^-$$
$$\Lambda^0 \rightarrow p \pi^-$$

another important discovery occurred at about the same time

Discovery of the ϕ(1020)

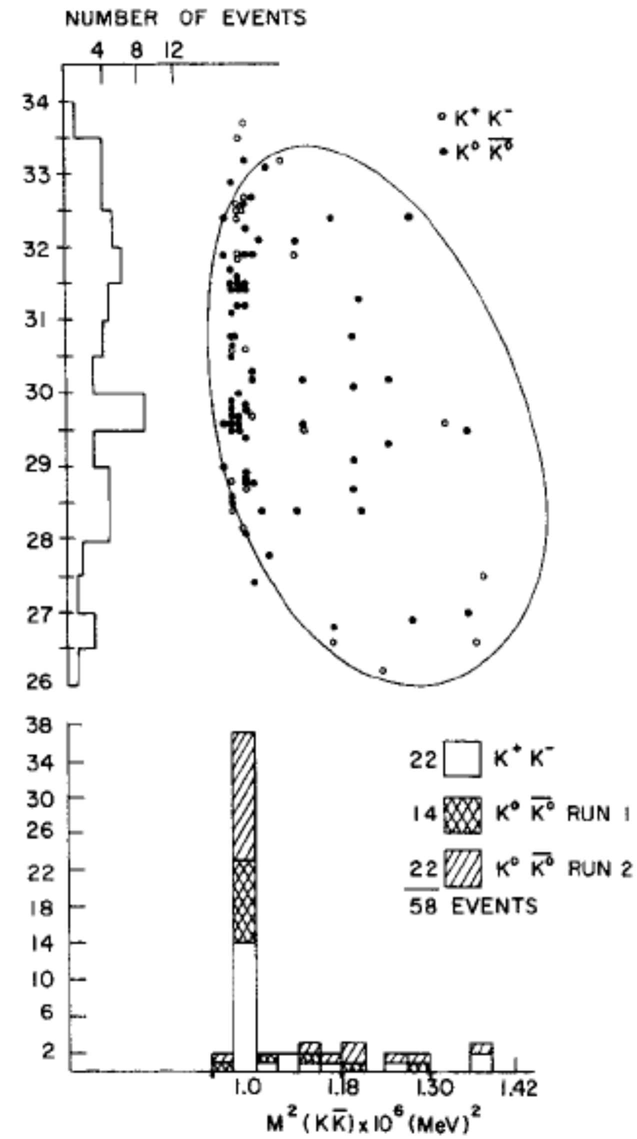
-- more important than the Ω^- ? --

Phys.Rev.Lett. 10, 134 (1963)

$$K^- p \to K^0 \overline{K}^0 n$$

$$K^- p \to K^+ K^- n$$

$\Leftarrow P_{K^-} = 2.23\ \text{GeV}$



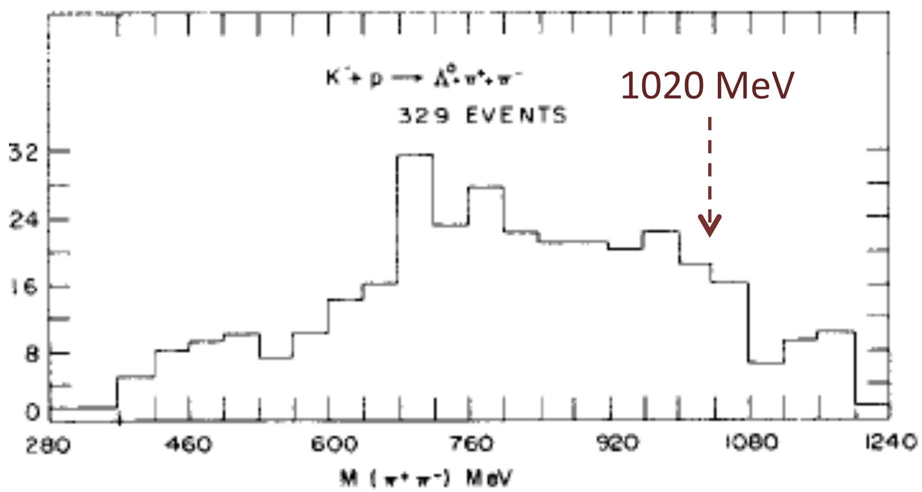
$M_\phi = 1019.5 \pm\ \text{MeV}$ ← well above 3π threshold

$\Gamma_\phi = 4.26 \pm 0.04\ \text{MeV}$ ← narrower than ω(782)

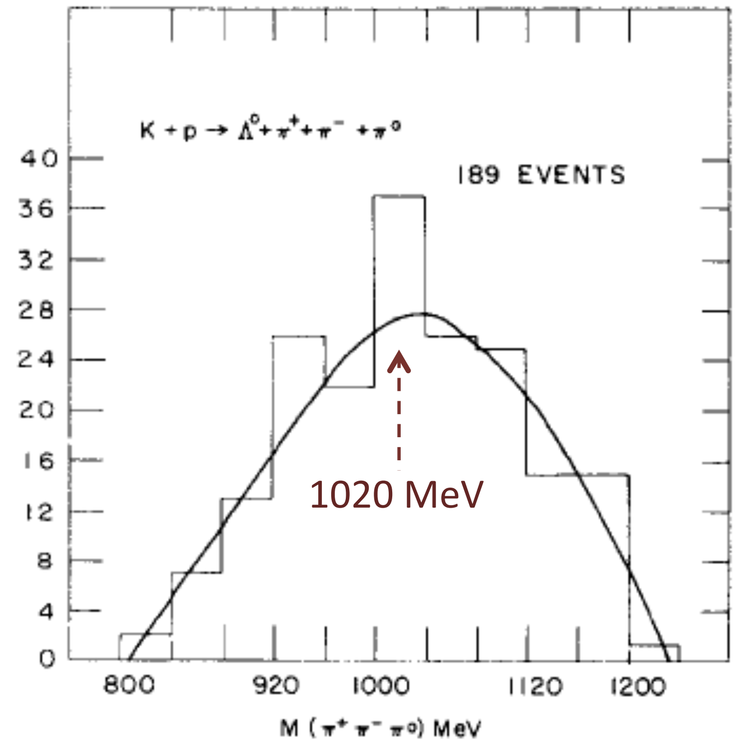
$J^P = 1^-$

$I = 0$

no $\phi \rightarrow \pi^+\pi^-$; $\phi \rightarrow \pi^+\pi^-\pi^0 < \phi \rightarrow K^+K^-$



For J=1⁻ and I=0. $\phi \rightarrow \pi^+\pi^-$ is forbidden



$$\frac{Bf(\phi \rightarrow \pi^+\pi^-\pi^0)}{Bf(\phi \rightarrow K^+K^-)} = 0.31 \pm 0.3$$

$\phi \rightarrow \pi^+\pi^-\pi^0$ is allowed and has lots of phase-space. Why is it suppressed relative to $\phi \rightarrow K^+K^-$, which has tiny phase-space?

what's the difference between the ω(782) and the ϕ(1020)?

Partial width: $$\Gamma(X \to Y + Z) \equiv Bf\,(X \to Y + Z) \times \Gamma^X_{\text{total}}$$

This is what theorists calculate --

same quantum numbers

$$\Gamma(\omega(782) \to \pi^+\pi^-\pi^0) \approx 7.5 \text{ MeV}$$

ω is 10 × larger

$$\Gamma(\phi(1020) \to \pi^+\pi^-\pi^0) \approx 0.65 \text{ MeV}$$

ϕ has more phase space

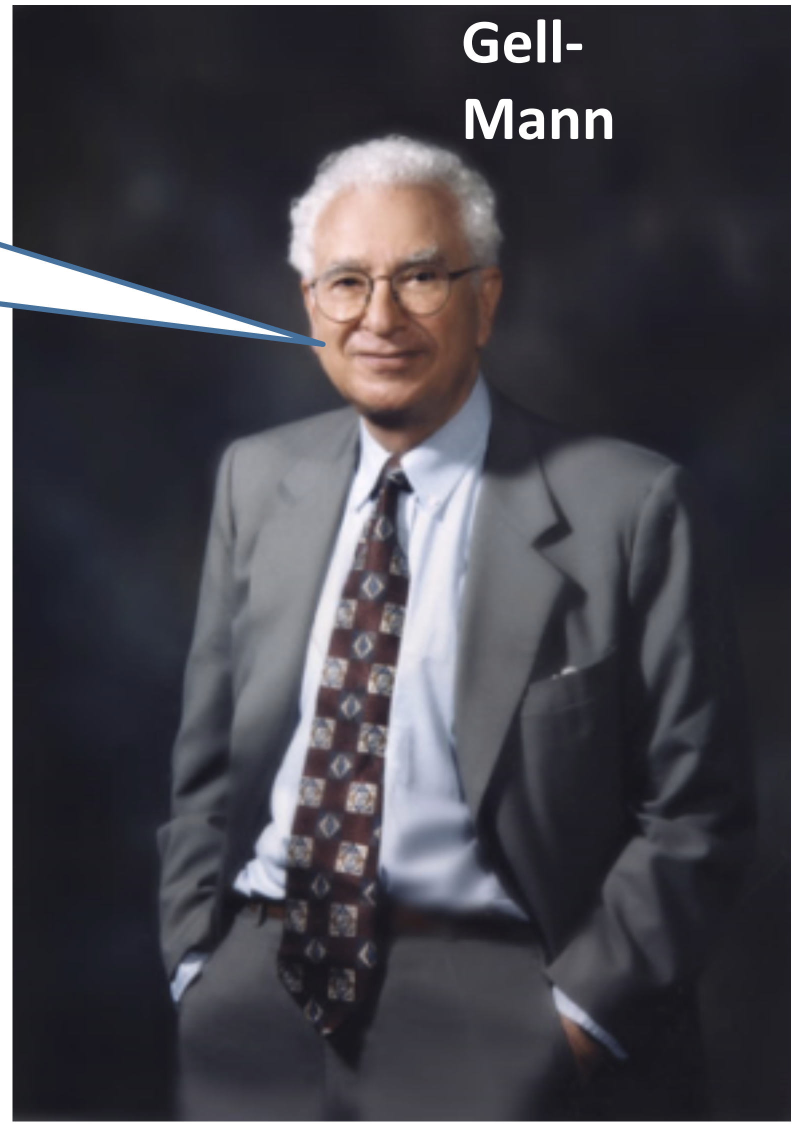
“totalitarian” principle

极权主义

What isn’t forbidden, is mandatory

不被禁止的都是强制性的

What enhances $\phi \rightarrow K^+K^-$ & suppresses $\phi \rightarrow \pi^+\pi^-\pi^0$?



early attempts to identify hadron constituents

1^{st} attempt to identify hadron constituents: Fermi-Yang

Fermi & Yang in 1949
(7 years before $\bar{p}$ discovery):
if $N\bar{N}$ potential is attractive, N & $\bar{N}$ could bind to form a π-meson.

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 76, No. 12 pg 1739 DECEMBER 15, 1949

Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received August 24, 1949)

The hypothesis that π-mesons may be composite particles formed by the association of a nucleon with an anti-nucleon is discussed. From an extremely crude discussion of the model it appears that such a meson would have in most respects properties similar to those of the meson of the Yukawa theory.

$$|\pi^+\rangle = |p\rangle|\bar{n}\rangle$$

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}\left(|p\rangle|\bar{p}\rangle + |n\rangle|\bar{n}\rangle\right)$$

$$|\pi^-\rangle = |n\rangle|\bar{p}\rangle$$

2^{nd} attempt to identify hadron constituents: Sakata

1956 Sakata   Sakata Model

All the hadrons are composite states of

p, n, Λ : Fundamental Triplet

$p\bar{n}$	$p\bar{\Lambda}$	$\Lambda p\bar{n}$	$\Lambda\Lambda\bar{n}$
π^+	K^+	Σ^+	Ξ^0

Courtesy of Sakata Memorial Archival Library

Shoichi Sakata
1911-1970

> It seems to me that the present state of the theory of new particles is very similar to that of the atomic nuclei 25 years ago.

> Supposing that the similar situation is realized at present, I proposed a compound hypothesis for new unstable particles to account for Nishijima-Gell-Mann's rule.

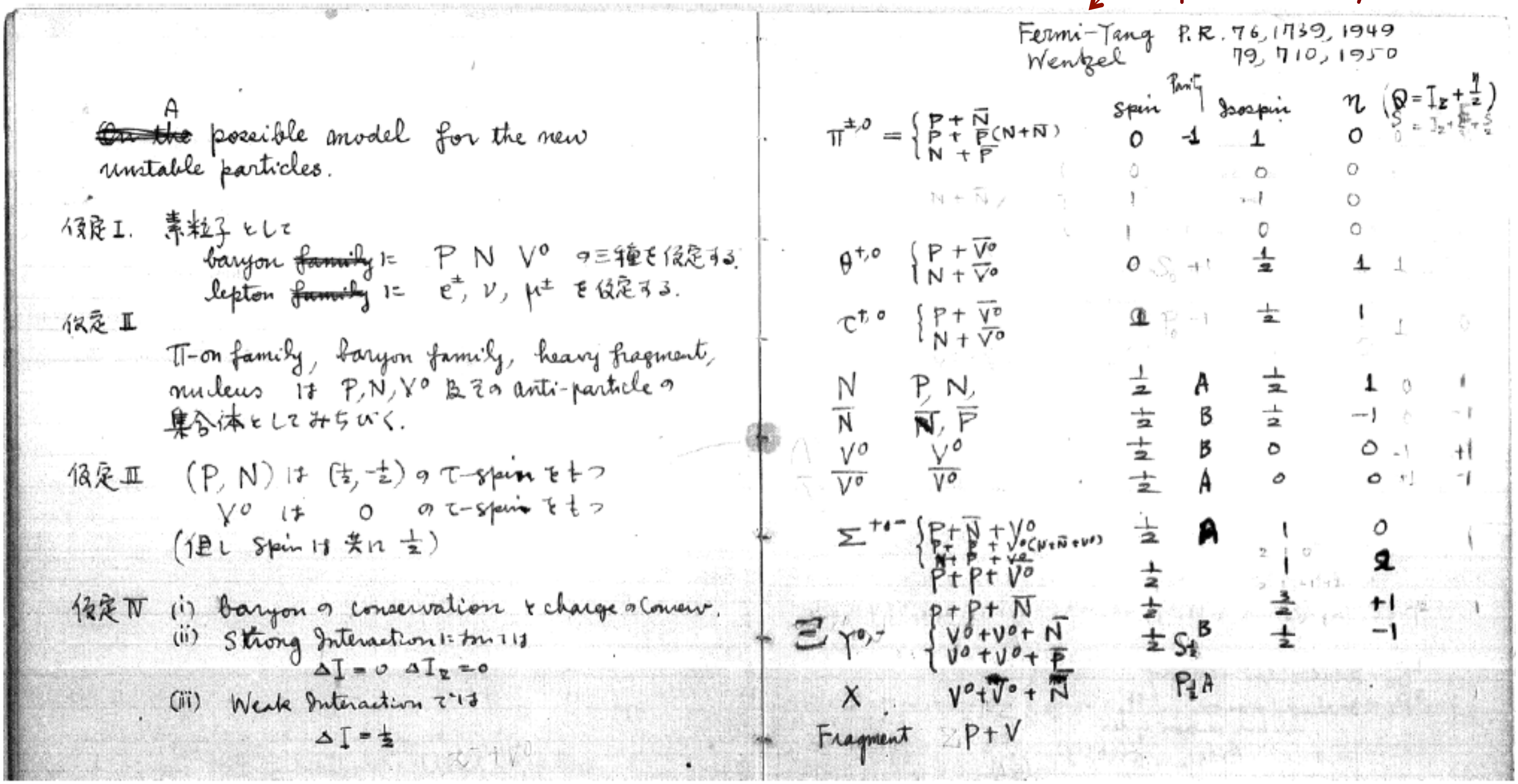
S. Sakata, Prog. Theor. Phys. **16** (1956), 686.

1959 Ikeda, Ogawa, Ohnuki

U(3) symmetry of the Sakata Moel

Sakata's Notebook

Fermi-Yang paper prominently cited



~~On the~~ A possible model for the new unstable particles.

仮定I. 素粒子として
baryon ~~family~~ に P N V^0 の三種を仮定する.
lepton ~~family~~ に $e^\pm$, ν, $\mu^\pm$ を仮定する.

仮定II
π-on family, baryon family, heavy fragment, nucleus は P, N, V^0 及その anti-particle の集合体としてみちびく.

仮定III (P, N) は $(\frac{1}{2}, -\frac{1}{2})$ の τ-spin をもつ
V^0 は 0 の τ-spin をもつ
(但し spin は共に $\frac{1}{2}$)

仮定IV (i) baryon の conservation と charge の conserv.
(ii) Strong interaction においては $\Delta I = 0$ $\Delta I_z = 0$
(iii) Weak interaction では $\Delta I = \frac{1}{2}$

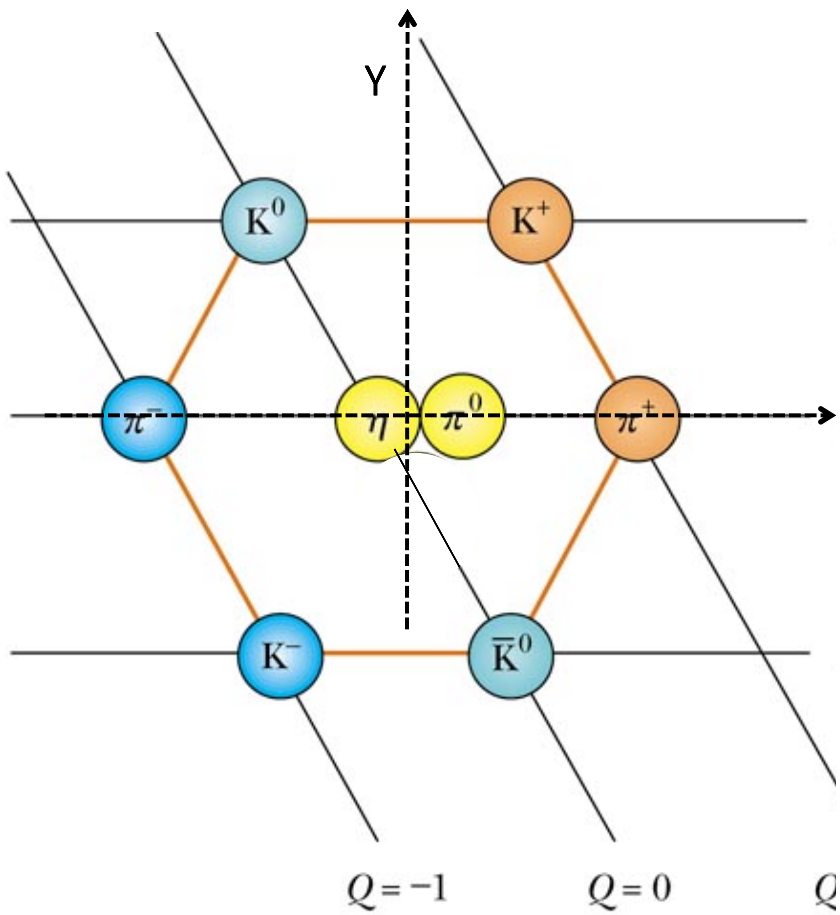
Fermi-Yang P.R. 76, 1739, 1949
Wentzel 79, 710, 1950

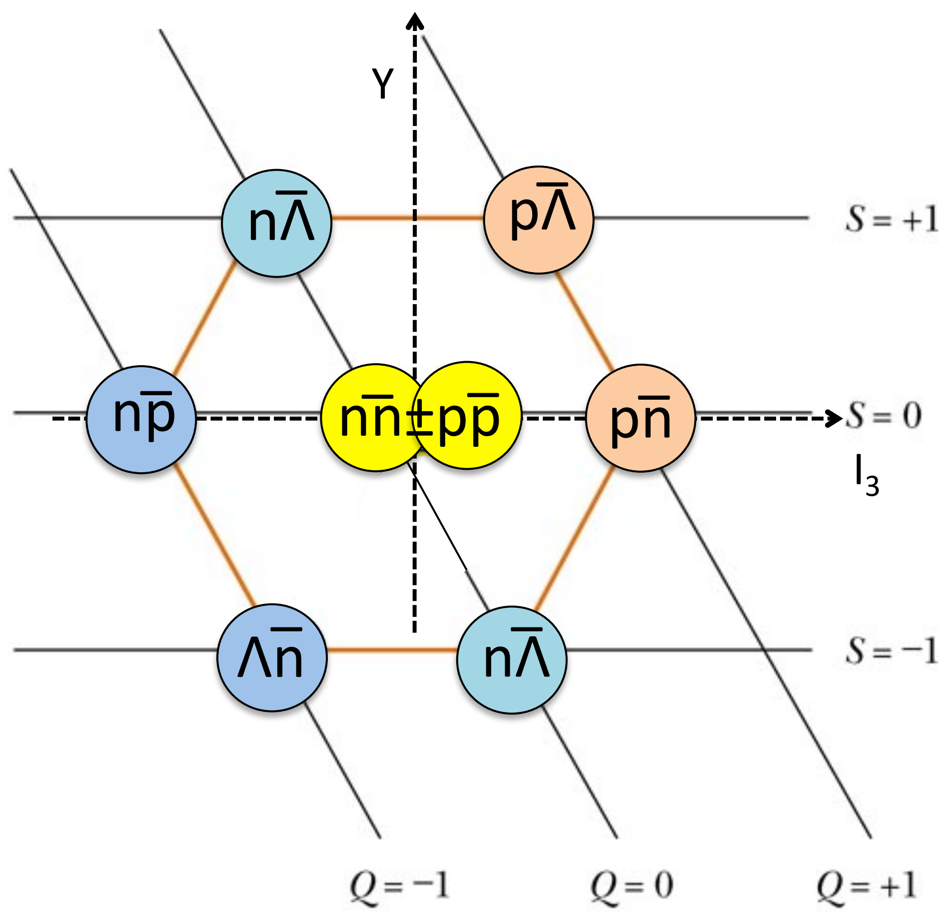
		Spin	Parity	Isospin	η $(Q = I_z + \frac{\eta}{2})$
$\pi^{\pm,0}$	$P+\bar{N}$, $P+\bar{P}$ $(N+\bar{N})$, $N+\bar{P}$	0	-1	1	0
$\theta^{+,0}$	$P+\bar{V}^0$, $N+\bar{V}^0$	0		$\frac{1}{2}$	1
$\tau^{+,0}$	$P+\bar{V}^0$, $N+\bar{V}^0$	0		$\frac{1}{2}$	1
N	P, N	$\frac{1}{2}$	A	$\frac{1}{2}$	1
$\bar{N}$	$\bar{N}$, $\bar{P}$	$\frac{1}{2}$	B	$\frac{1}{2}$	-1
V^0	V^0	$\frac{1}{2}$	B	0	0
$\bar{V}^0$	$\bar{V}^0$	$\frac{1}{2}$	A	0	0
Σ^{+0-}	$P+\bar{N}+V^0$, $P+\bar{P}+V^0$ $(N+\bar{N}+V^0)$, $N+\bar{P}+V^0$	$\frac{1}{2}$	A	1	0
	$P+P+\bar{V}^0$	$\frac{1}{2}$		1	2
	$P+P+\bar{N}$	$\frac{1}{2}$		$\frac{3}{2}$	+1
Ξ $Y^{0,-}$	$V^0+V^0+\bar{N}$, $V^0+V^0+\bar{P}$	$\frac{1}{2}$	B	$\frac{1}{2}$	-1
X	$V^0+\bar{V}^0+\bar{N}$		P A		
Fragment	$\Sigma P+V$				

Sakata calls the Λ^0 and the K mesons by their old names: V^0, $\theta^{+,0}$ and $\tau^{+,0}$

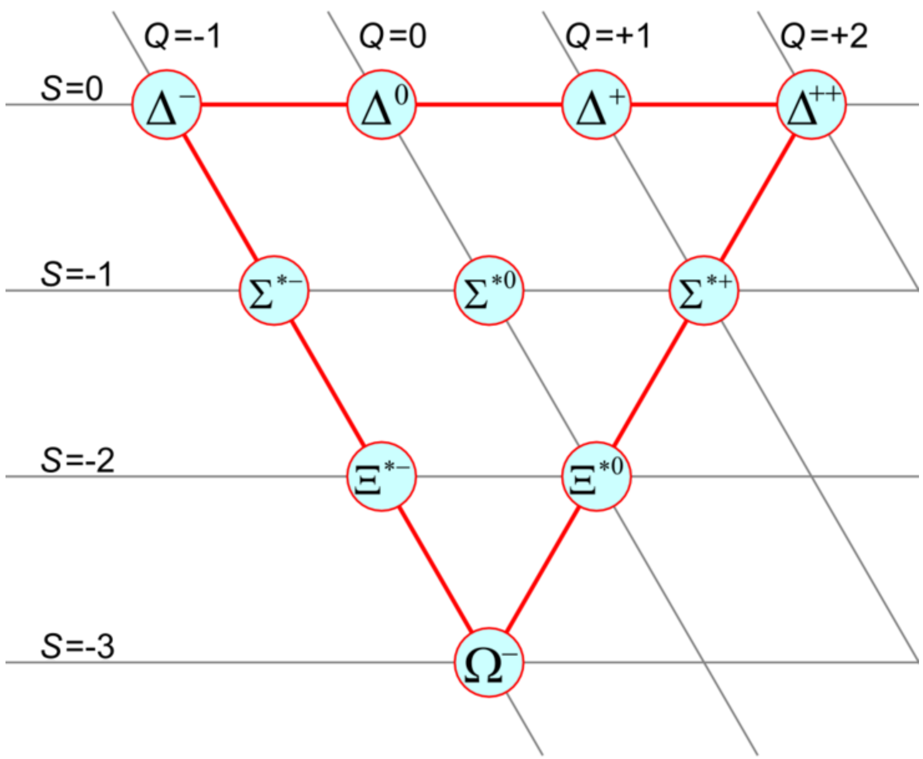
Sakata model produce the meson octets

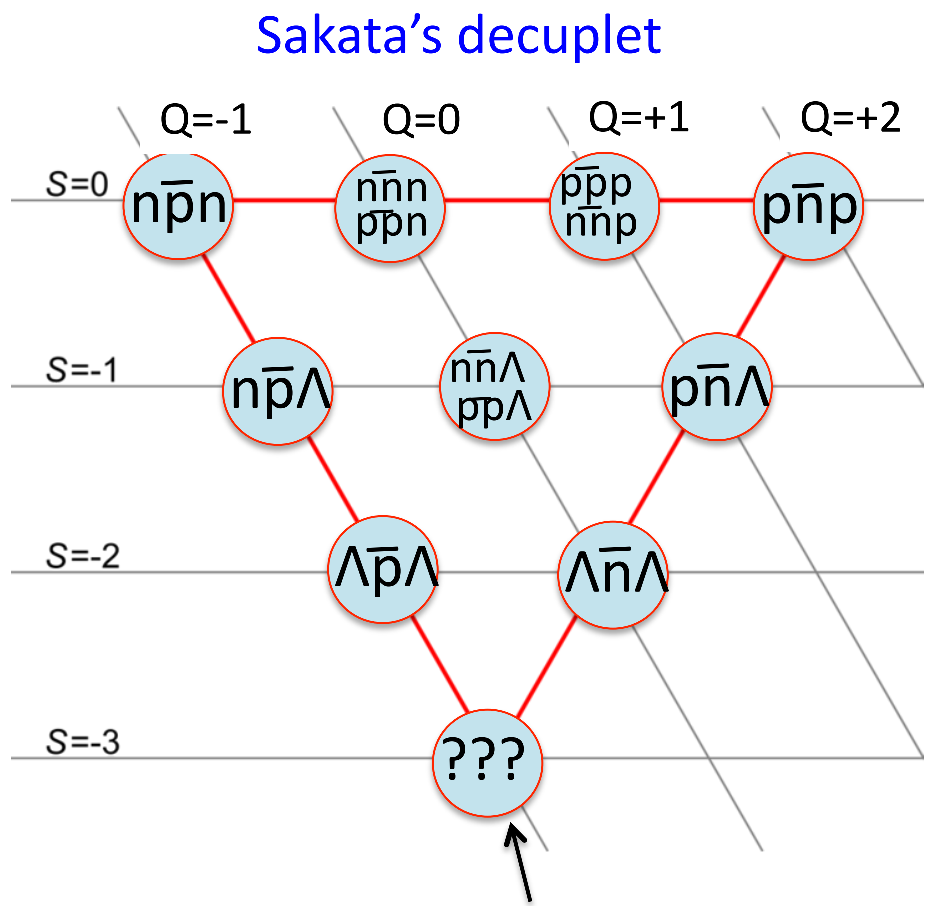
$J^P=0^-$ meson octet





but the baryon decuplet has problems

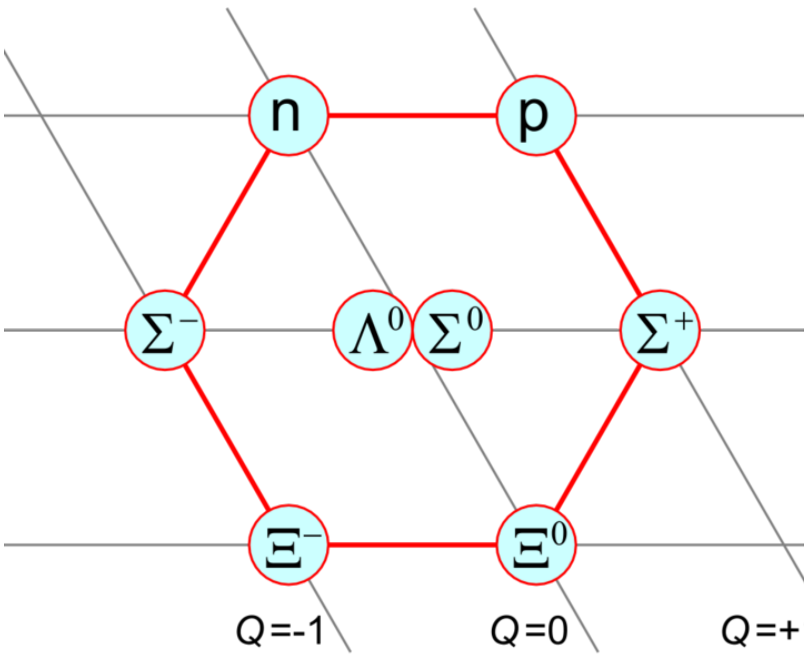




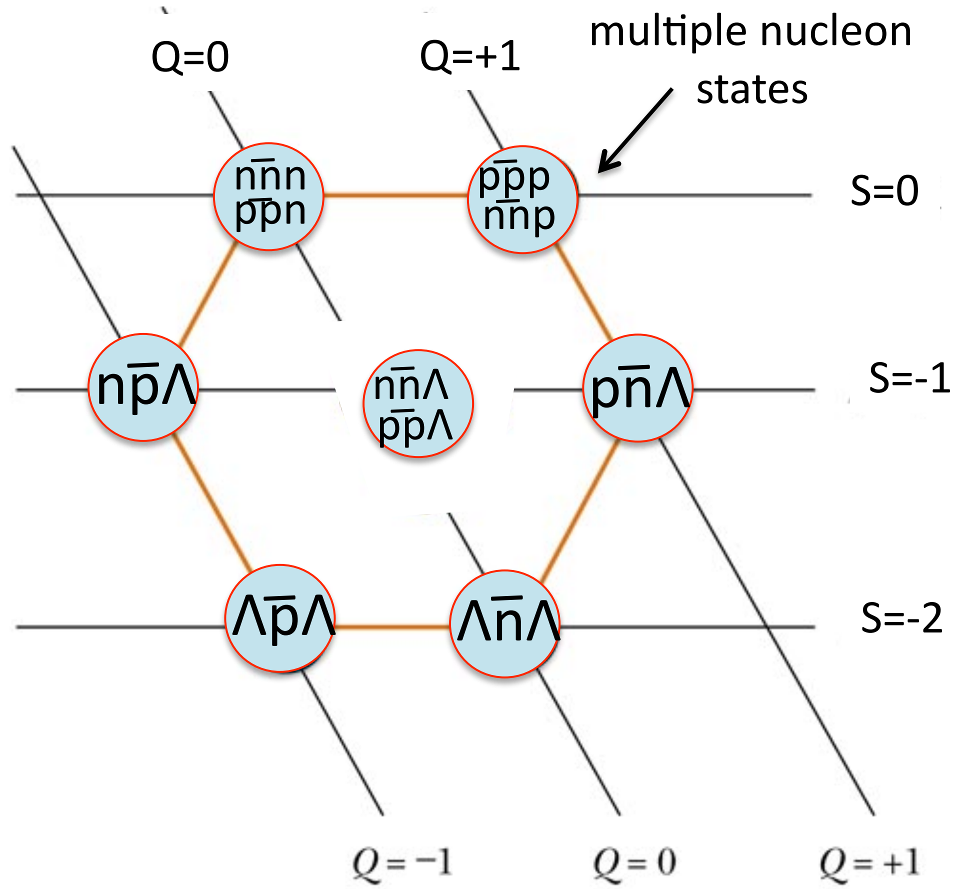
mass splitting is uniform and ≈m_Λ-m_N=175 MeV, not so bad

for S=-3, need ΛΛΛ but ΛΛΛ has Q=0

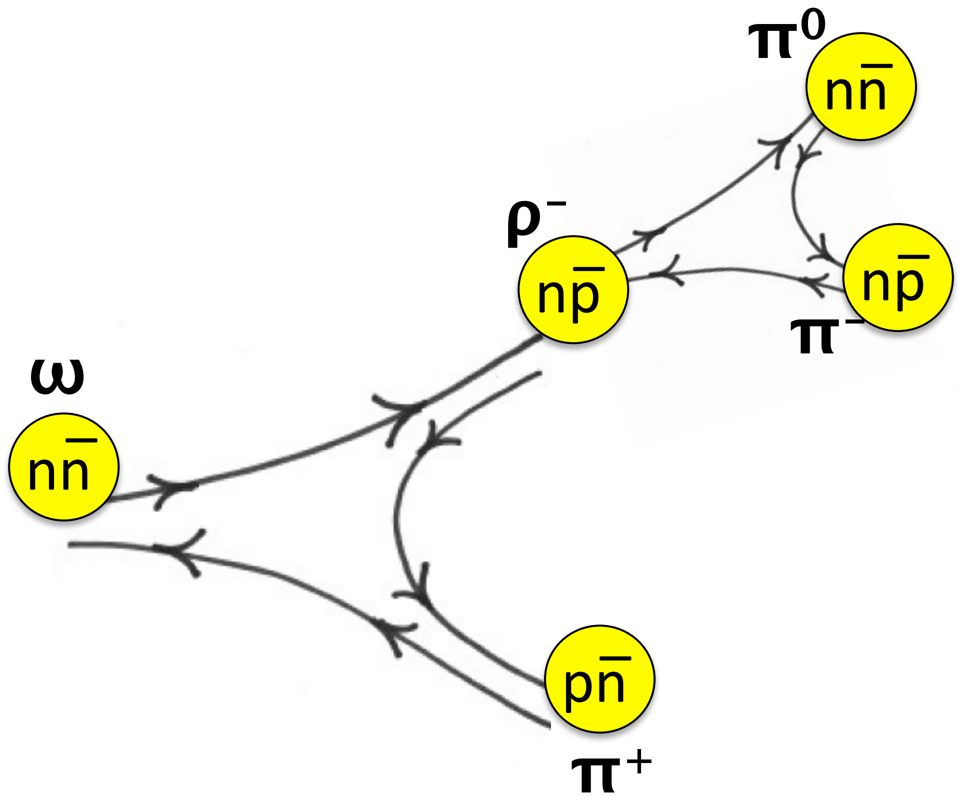
Sakata's baryon octet is a little peculiar



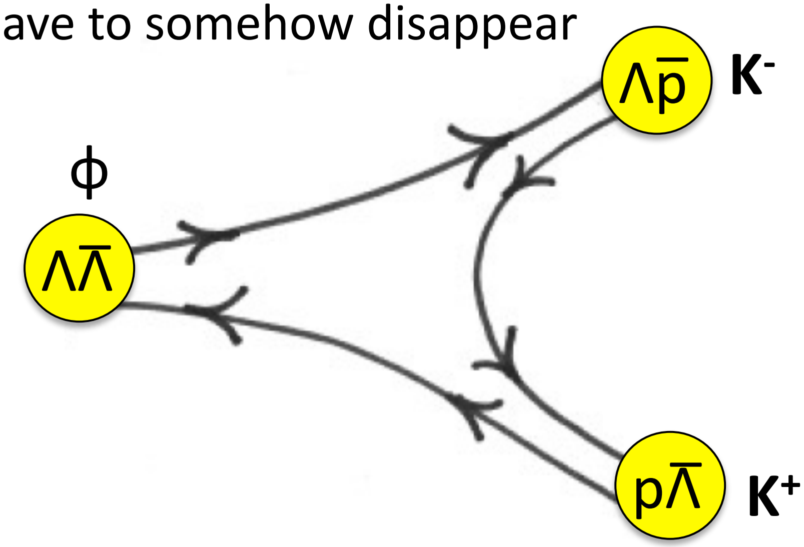
Sakata's baryon octet



Sakata also explains why $\phi \rightarrow K^+K^-$ and $\omega \rightarrow \pi^+\pi^-\pi^0$

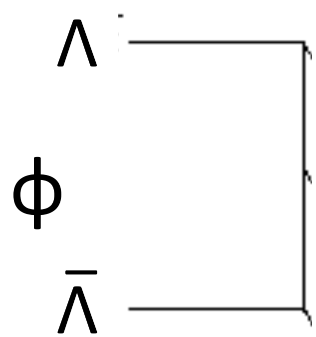


for $\phi \rightarrow \pi^+\pi^-\pi^0$, the initial Λ and $\bar{\Lambda}$ have to somehow disappear

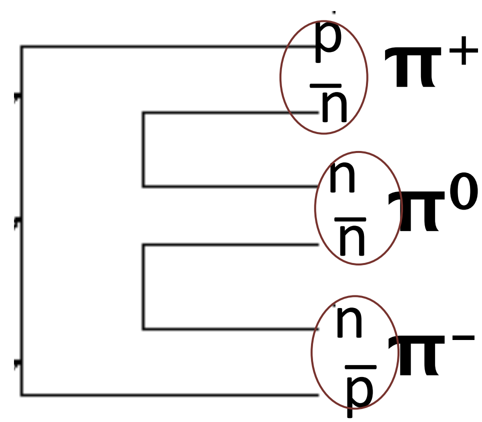


OZI suppression

initial state



initial state



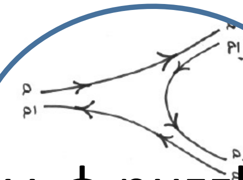
processes in which there are no constituent lines connecting the initial &final states are suppressed

Comments on the Sakata model

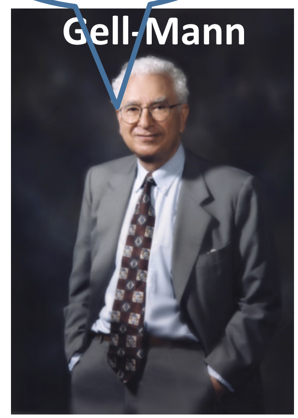
- It reproduces the meson octets
- it can explain the ϕ-ω puzzle
- It can produce baryon octets and decuplets, but with some S=-3 state charge shifted by ΔQ=+1
- It treats the p. n and Λ as special, for no obvious reason
- It contains some truth but it is not the whole story

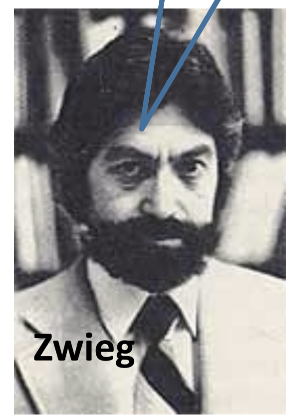
Quarks (Aces?)

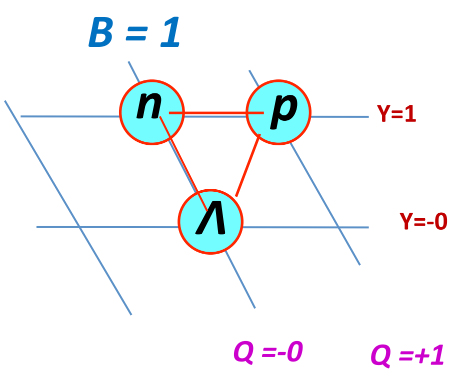
SU(3)-group structure "Quarks"

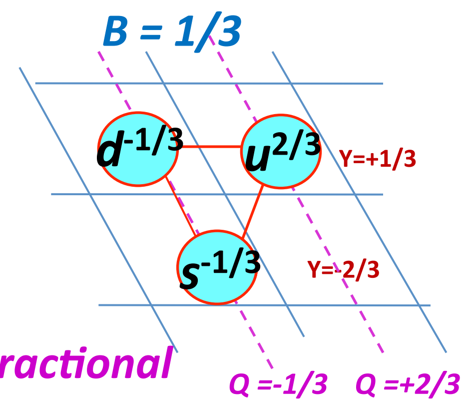


ω-ϕ puzzle "Aces



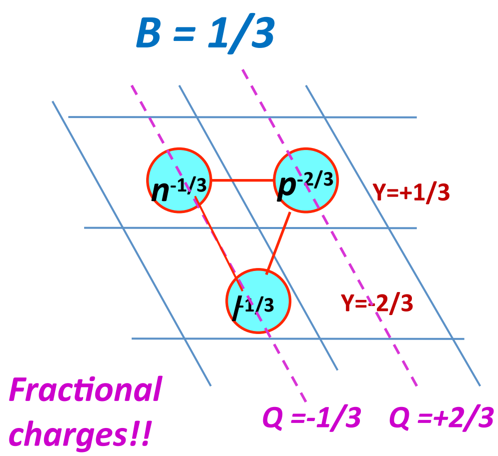


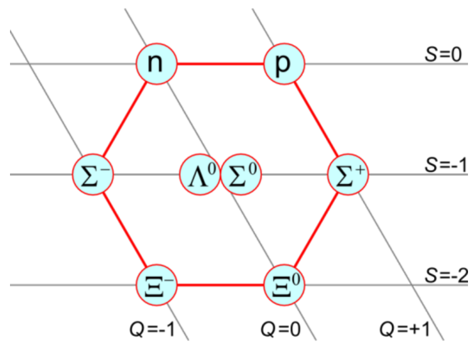


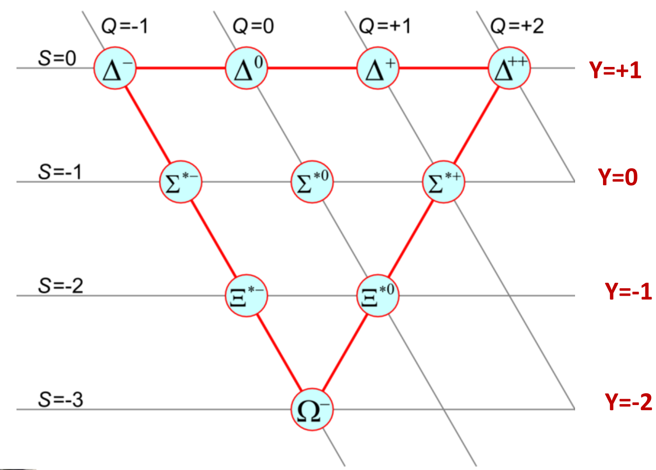


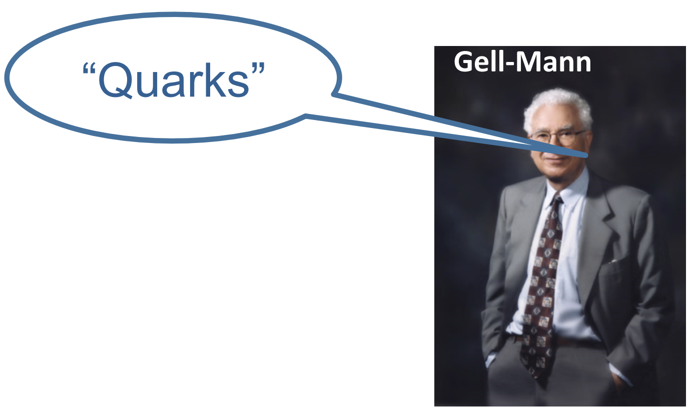
Fractional charges!!

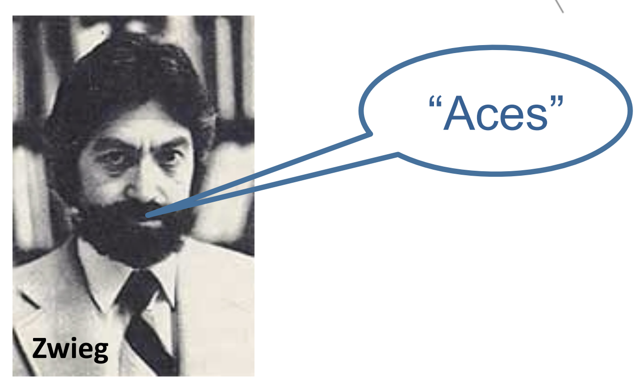
1964: triplet = the most fundamental representation of SU(3)





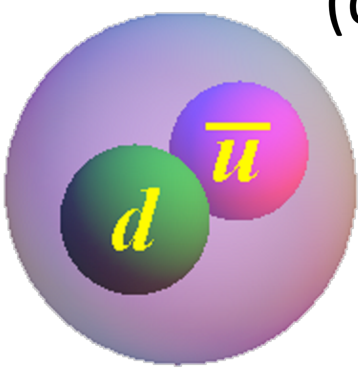






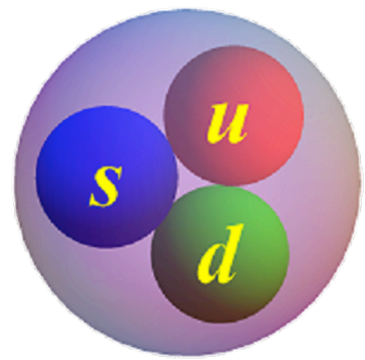
Textbooks: Quark-Parton-Model

mesons = quark-antiquark
($q\bar{q}$)



$\pi^- = (d\bar{u})$

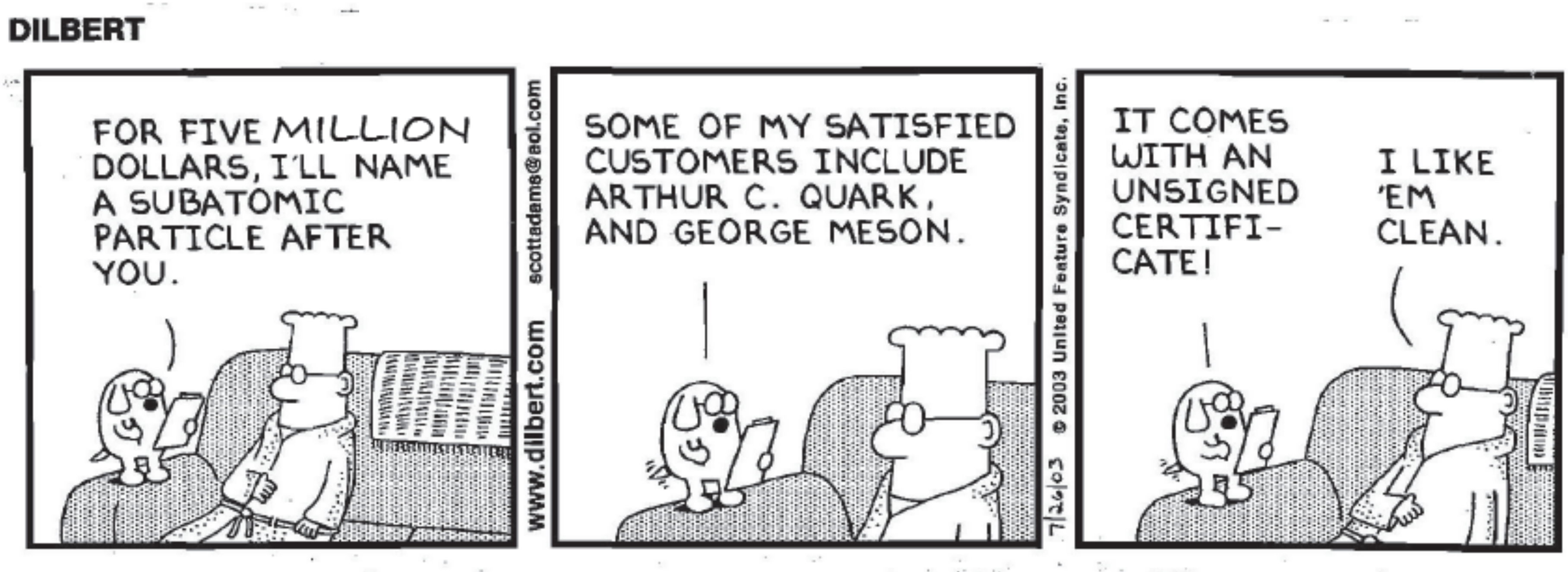
baryons = quark-quark-quark
(qqq)



$\Lambda = (uds)$

Fabulously successful

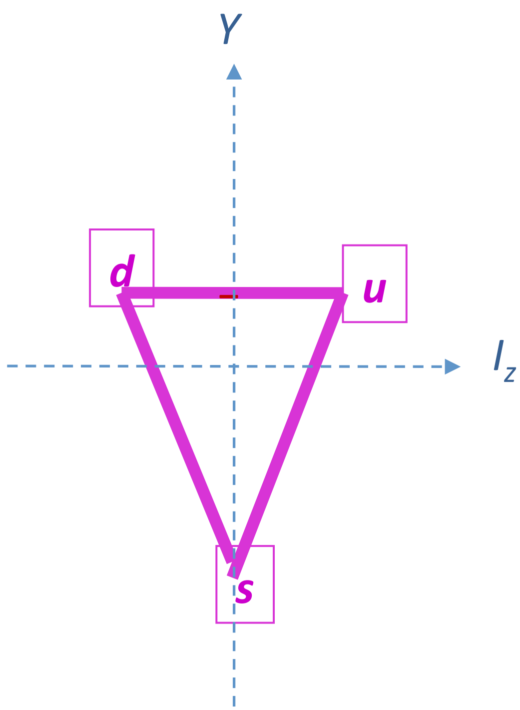
Quarks are probably the most
well known particle physics quantity
among the general public

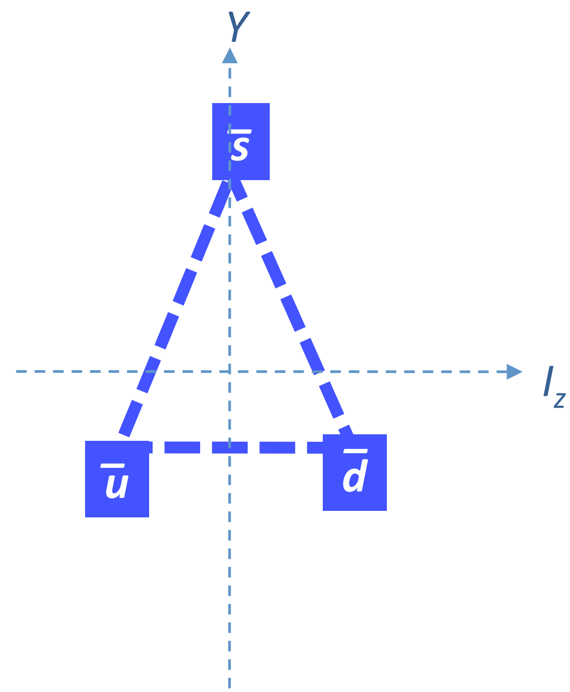


Google Search: quark: 25,500,000 results

Yao Ming: 17,300,000 results

Quarks & Antiquarks in I_z-Y space



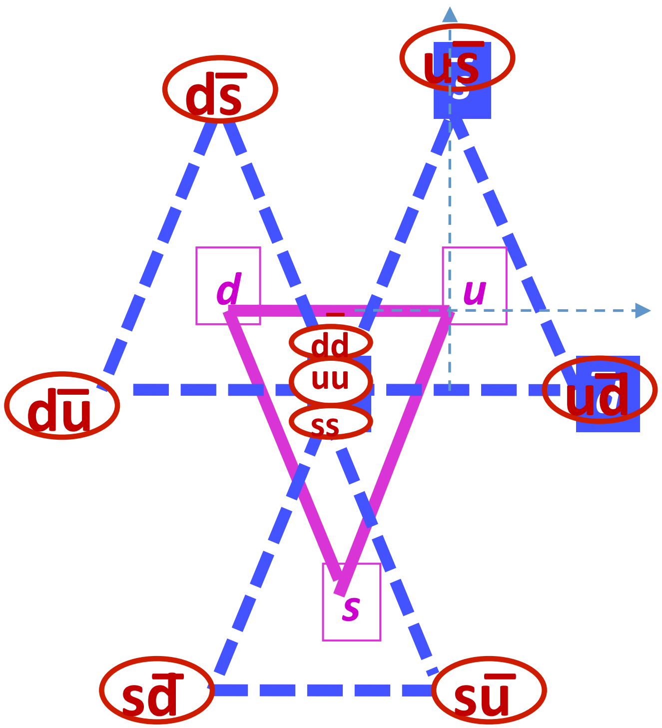


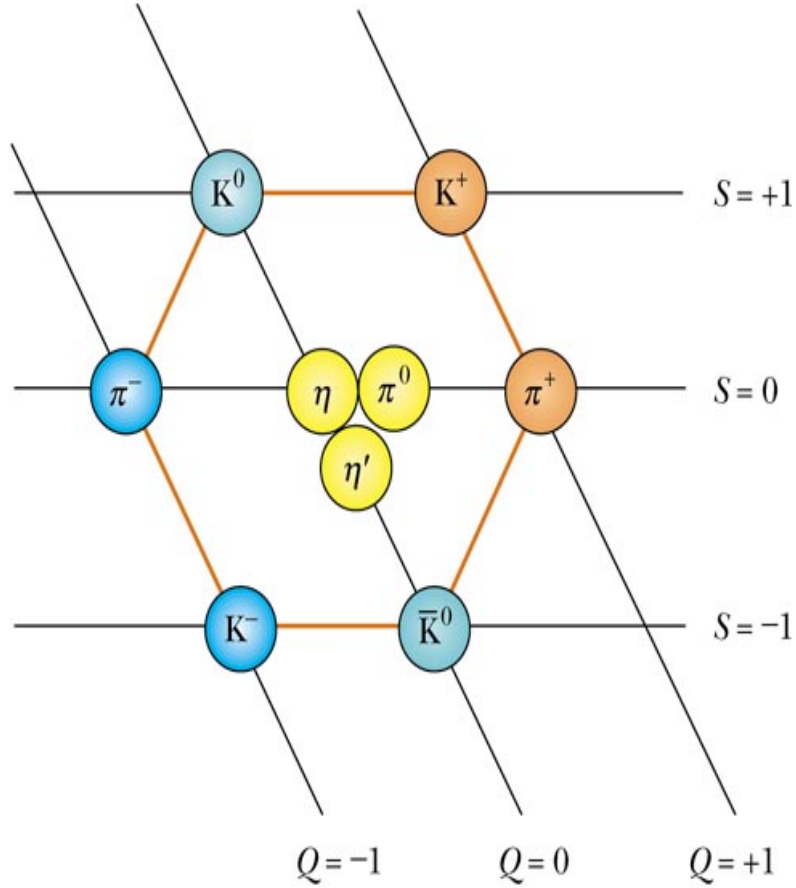
I_z = z component of Isospin

Y=hypercharge (=Baryon# + Strangeness)

quarks have Baryon#=⅓

Make mesons from quark-antiquark



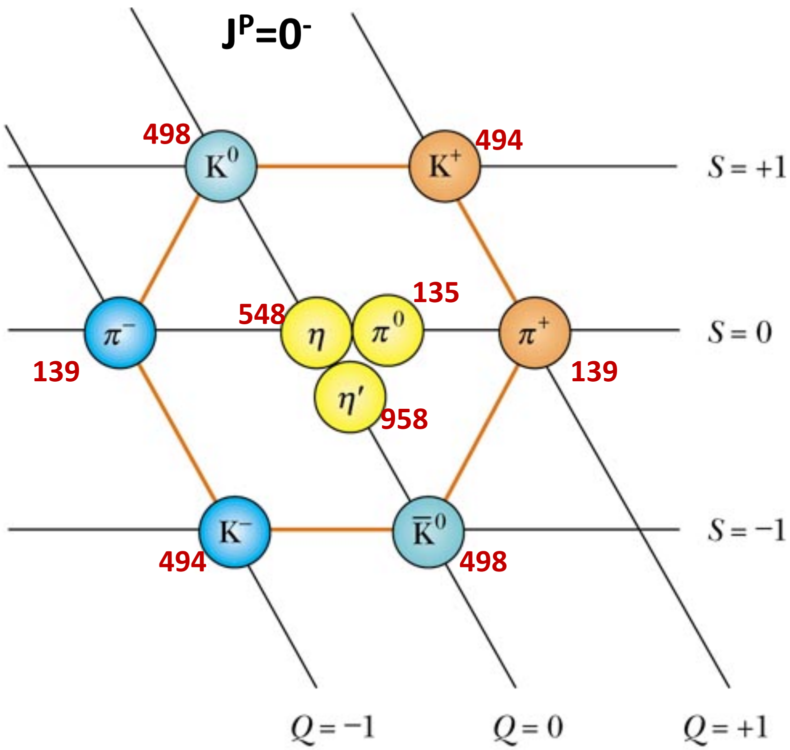


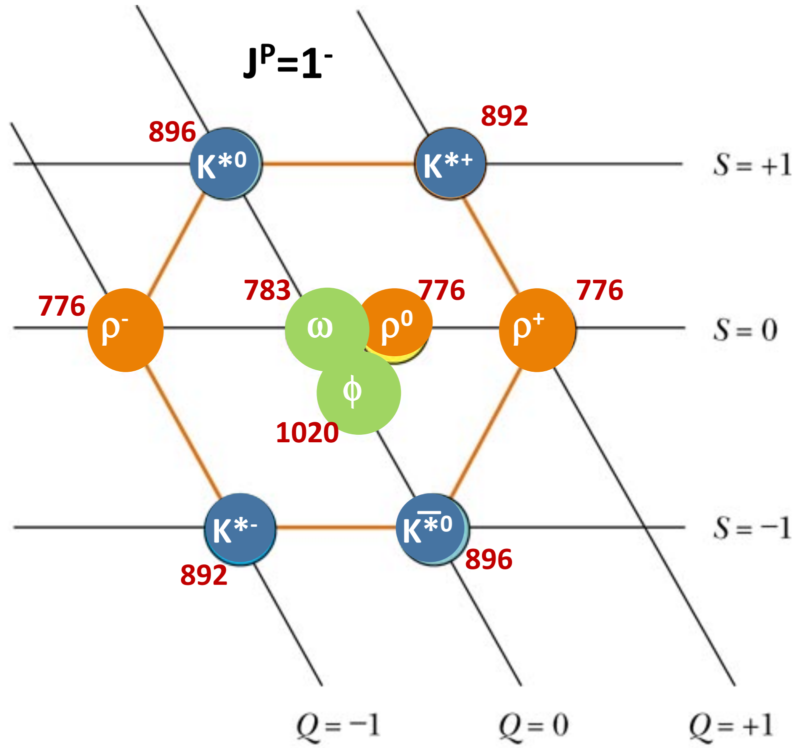
Q=electric-charge (=I_z+Y/2)

9 states: $$3 \otimes \bar{3} = 1 \oplus 8$$

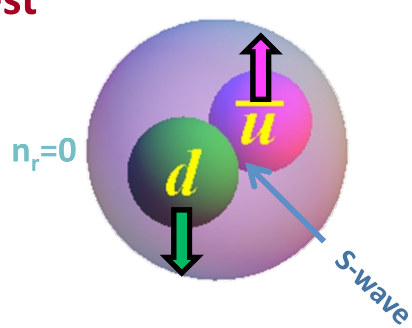
SU(3) singlet
+ SU(3) octet

Ground state mesons

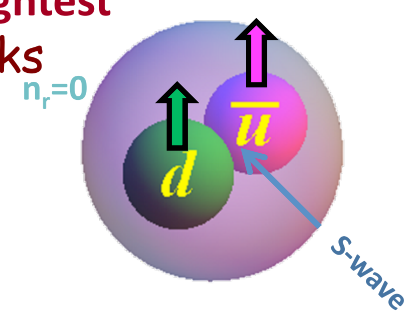




(π^+,π^0,π^-)=lightest
no s-quarks



(ρ^+,ρ^0,ρ^-)=lightest
no s-quarks

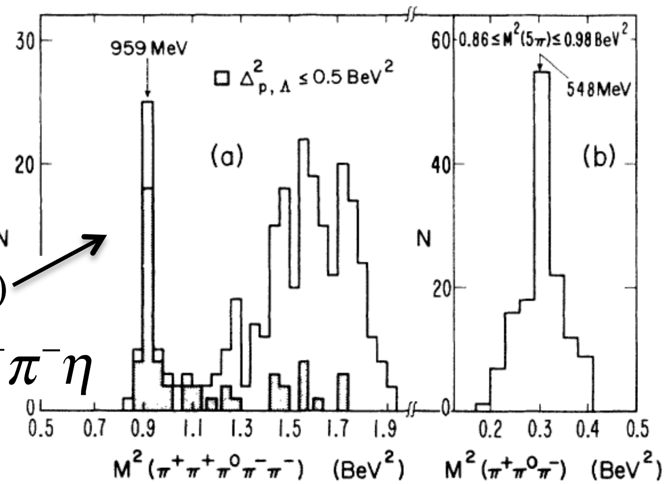


Discovery of the η′ meson

Phys.Rev.Lett. 12, 527 (1964)

Berkeley 72" BC

$$K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^+ + \pi^- + \pi^0,$$



$K^- p \rightarrow \Lambda^0 \eta'(958)$

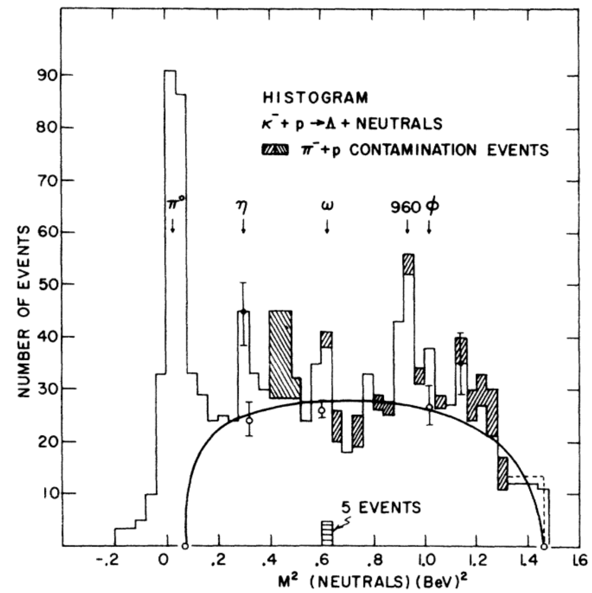
└→ $\pi^+\pi^-\eta$

$\eta \rightarrow \pi^+\pi^-\pi^0$

Phys.Rev.Lett. 12, 546 (1964)

Brookhaven 80" BC

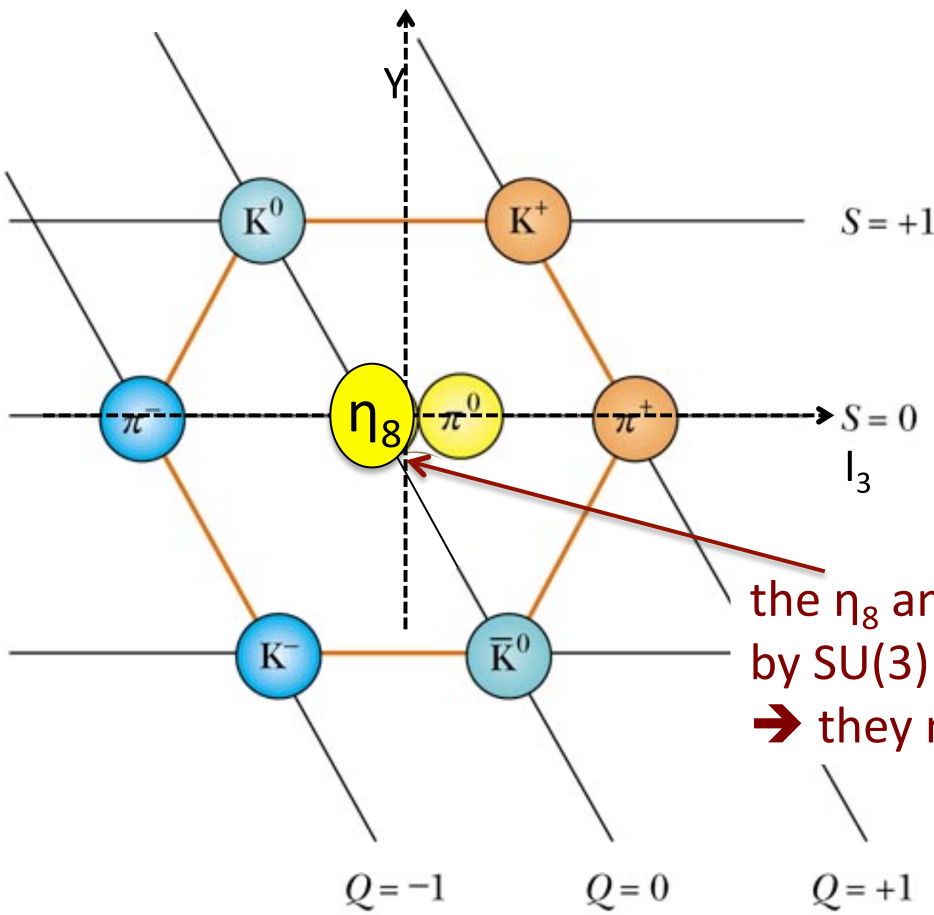
$$K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^+ + \pi^- + \pi^0,$$



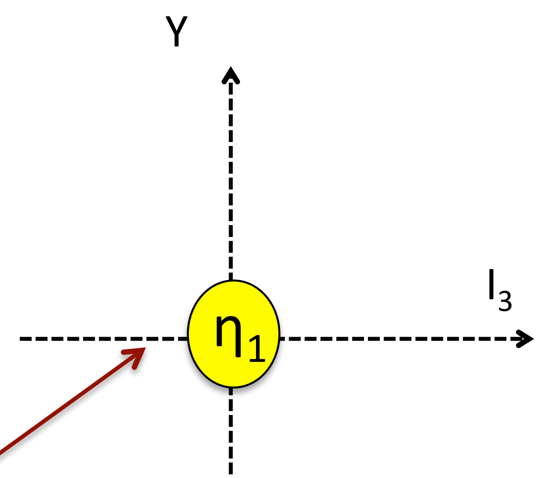
M=957.8 ±1 MeV Γ=0.20 ±0.01 MeV $J^P=0^-$

meson “nonet” = octet + singlet

J^P=0$^-$ meson octet



J^P=0$^-$ meson singlet



the η_8 and η_1 differ only by SU(3) quantum numbers

➔ they mix

η-η'mixing

SU(3) has two η-mesons, an "octet" η_8, and a singlet η_1, where:

$$\eta_1 = \tfrac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right)$$

$$\eta_8 = \tfrac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

However, SU(3) is a broken symmetry, so η_1 an η_8 "mix". Thus the physical η and η' mesons are each mixtures of η_1 and η_8 :

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\theta_P & \sin\theta_P \\ -\sin\theta_P & \cos\theta_P \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_8 \end{pmatrix},$$

where θ_P is the "pseudoscalar mixing angle." The range of of allowed values is:

$$\theta_P = -11^o \Leftrightarrow -25^o$$

For θ_P=-9.7^o, the η & η' have same $s\bar{s}$ and $(u\bar{u}+d\bar{d})/\sqrt{2}$ content (with opposite relative sign).

ω-ϕ mixing

The ω and ϕ also mix, but in this case θ_V, the "vector mixing angle" is large and positive:

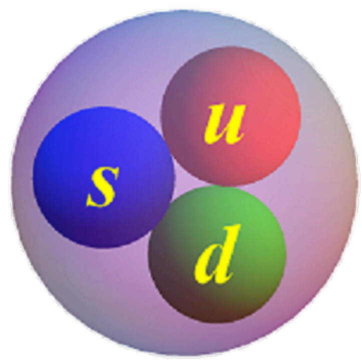
$$\theta_V \approx 37^o$$

this is very close to the "ideal" mixing angle

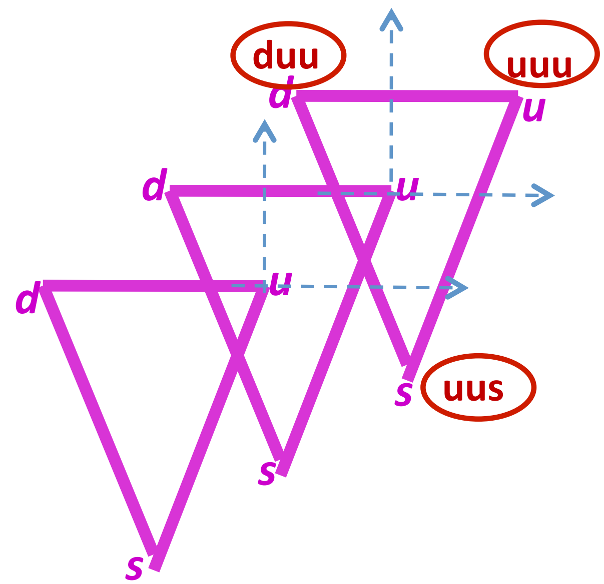
$$\theta_V^{\text{ideal}} = \arctan(1/\sqrt{2}) = 35.3^o$$

in which case the ϕ-meson would be 100% $s\bar{s}$ while the ω-meson would be 100% $(u\bar{u}+d\bar{d})/\sqrt{2}$. In fact the $s\bar{s}$ content of the ω is about 3% of $(u\bar{u}+d\bar{d})/\sqrt{2}$.

How about the baryons=qqq model?

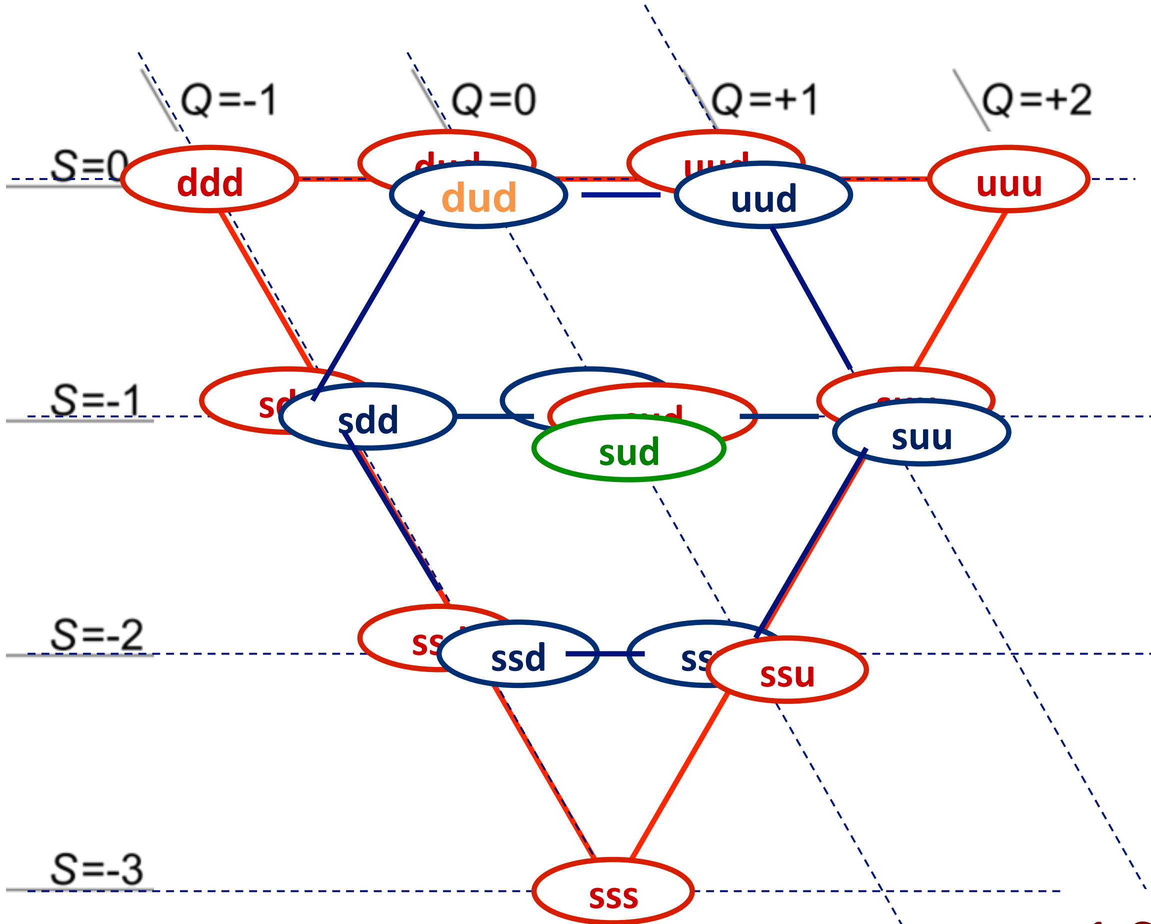


Make baryons from 3 quarks



HW: Finish the procedure

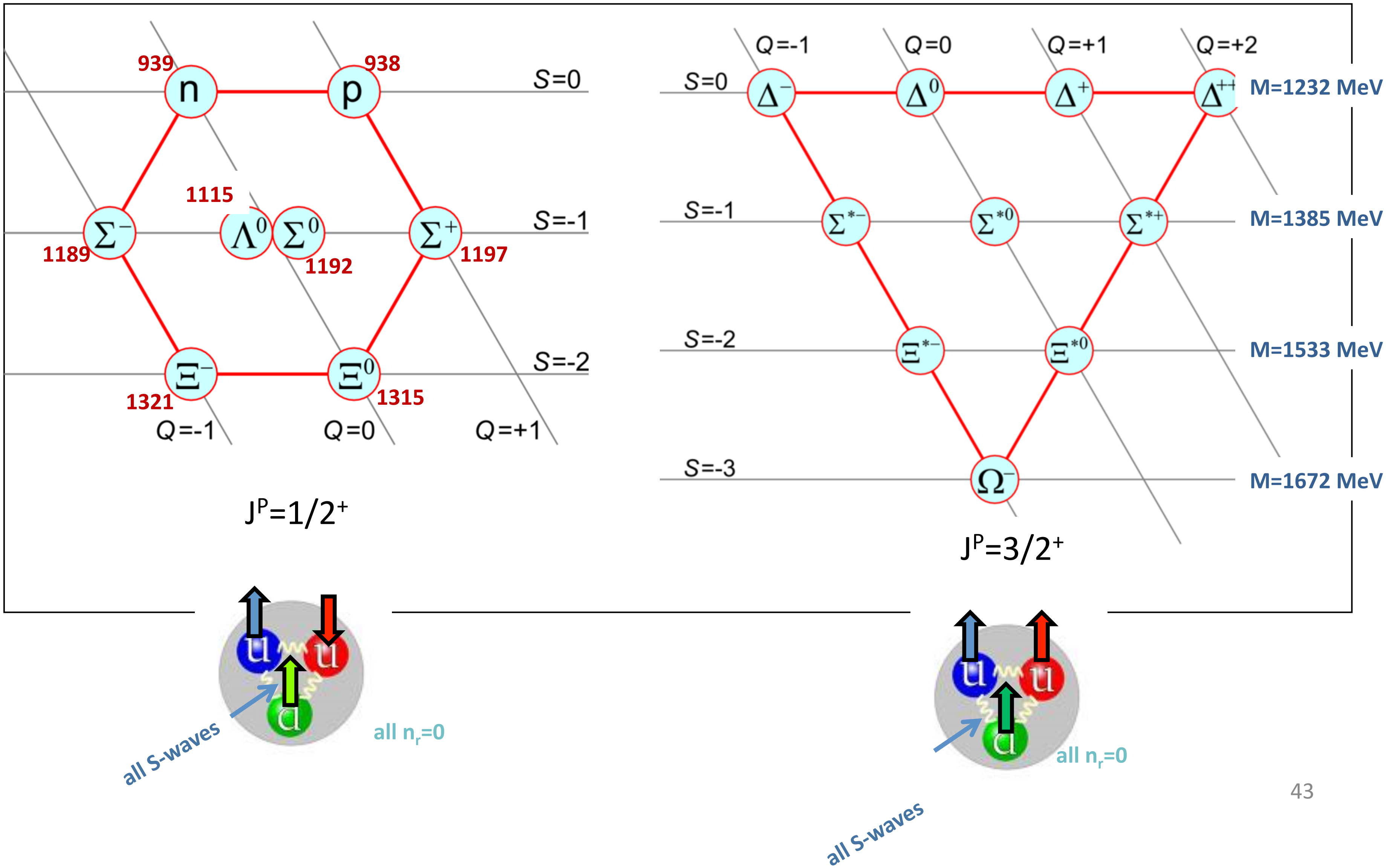
Answer



27 states: $3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$

1 SU(3) decuplet
+2 SU(3) octets
+1 SU(3) singet

Ground state Baryons



Summary (lecture 2)

- The fractionally charged quark model does a good job at explaining then patterns and properties of the ground state mesons and baryons.

- The $q\bar{q}$=mesons and qqq=baryon prescriptions work well for the lowest-lying mesons & baryons, but fail otherwise

Discussion/HW items

Why is $\phi(1020) \rightarrow \pi\pi$ forbidden?

In octet-singlet meson mixing there are two extreme cases:

--in one, called "Ideal mixing," one of the physical mesons is purely $s\bar{s}$, while the other is purely $(u\bar{u}+d\bar{d})/\sqrt{2}$.

--in the other extreme, the two physical mesons have equal $s\bar{s}$ and $(u\bar{u}+d\bar{d})/\sqrt{2}$ content, with opposite relative sign.

Show that ideal mixing occurs when the mixing angle $\theta=35.3^o$ and the equal $s\bar{s}$-content cases occurs when $\theta=-9.7^o$.