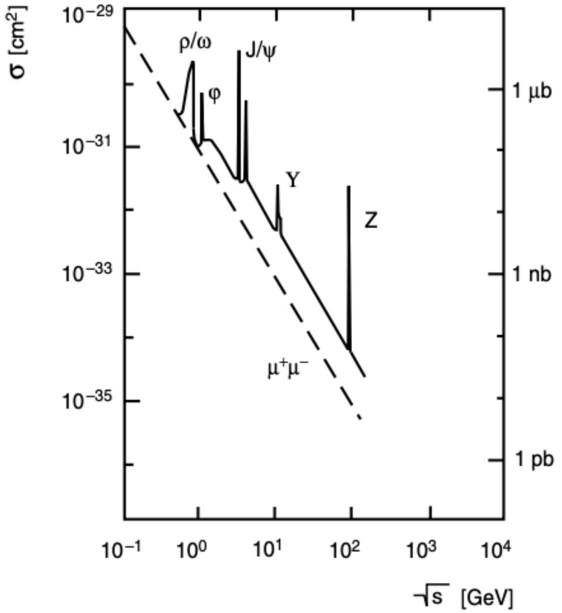
Discovery of ρ, ω, ϕ and further resonances (1952 – 1964)

Liverpool Muon Group Seminar

Cedric

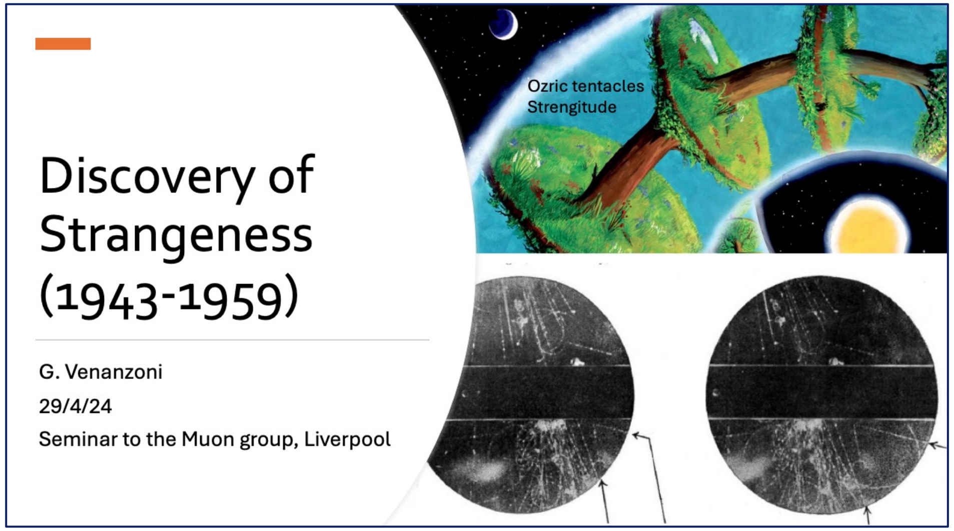
21 May 2024



From ‘particles’ to ‘resonances’

Particles

- lifetime $\tau = 10^{-10}\mathrm{s}$
- A visible distance in a **bubble chamber** or **emulsion** before decaying



Ozric tentacles
Strengitude

Discovery of Strangeness (1943-1959)

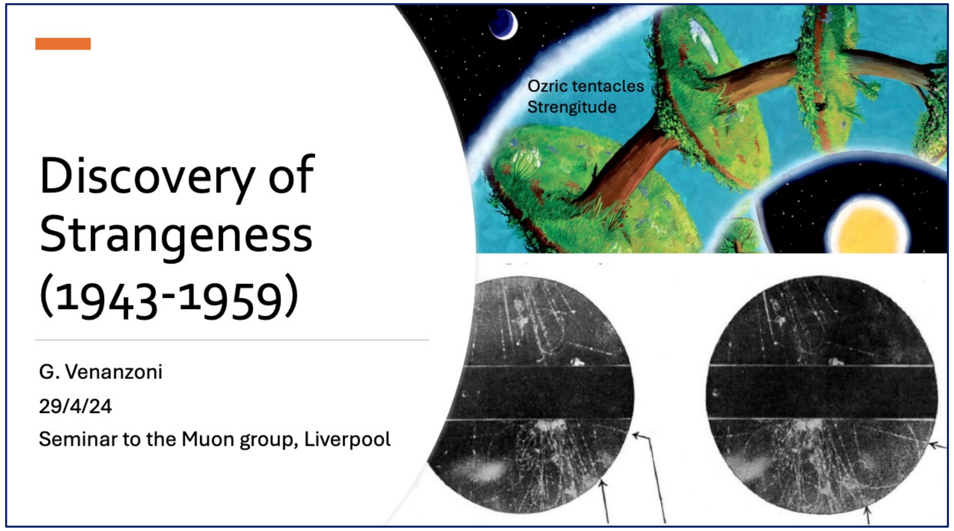
G. Venanzoni
29/4/24
Seminar to the Muon group, Liverpool

https://indico.ph.liv.ac.uk/event/1621/

From ‘particles’ to ‘resonances’

Particles

- lifetime $\tau = 10^{-10}\mathrm{s}$
- A visible distance in a **bubble chamber** or **emulsion** before decaying



Discovery of Strangeness (1943-1959)

G. Venanzoni

29/4/24

Seminar to the Muon group, Liverpool

https://indico.ph.liv.ac.uk/event/1621/

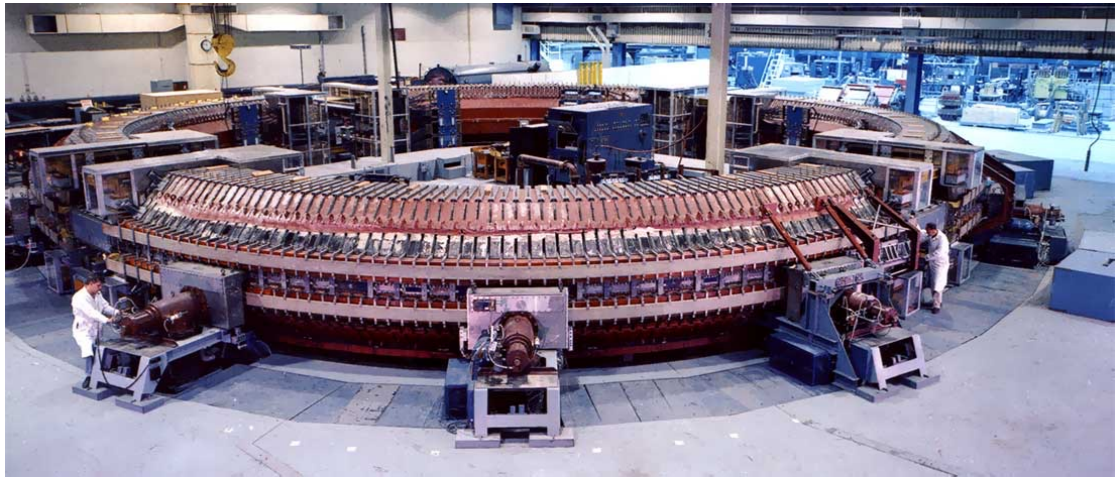
Resonances

- E width (10 – 200 MeV)
- $\tau = \hbar / 100\ \mathrm{MeV} \approx 10^{-25}\mathrm{s}$
- **Particle accelerators** (with liquid H bubble chamber)
- Fixed mass and well-defined quantum numbers
- Eventually, discovering these resonances reveals the deeper level of particles → quarks!

Technologies during this period

Accelerators

- Cosmotron (‘Cosmitron’): 1952 – 1966 @ BNL; proton to 3.3 GeV
    - The first accelerator in the world to accelerate particles to GeV (BeV).
- Bevatron: 1954 – 1993 @ LBNL



Technologies during this period

The liquid hydrogen bubble chamber

- Alvarez invented a new liquid H bubble chamber to detect the decay particles from the accelerator.
- He also developed new measurement systems and computer-based methods for analysing large data.
- Nobel Prize in 1968:

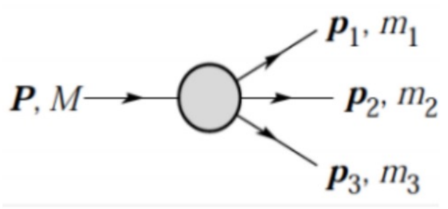
> *"for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using hydrogen bubble chamber and data analysis"*

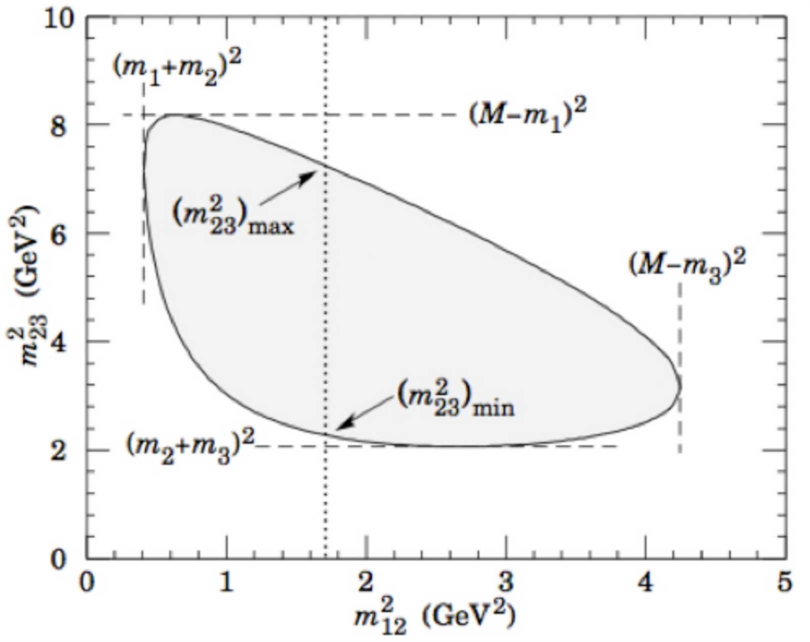
Luis Walter Alvarez

Technologies during this period

Analysis method: Dalitz plot

- A visual representation of the phase-space of a **three-body decay**. It is named after its inventor, Richard Dalitz (1925–2006).





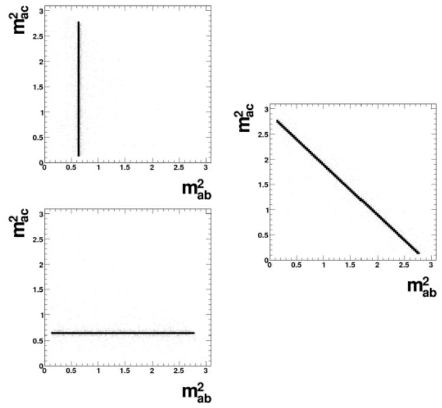
$$(m_i^2 + m_j)^2 \le m_{ij}^2 \le (M - m_k)^2$$

Non-uniformities in a Dalitz plot provide invaluable insights into the nature of a two-body resonance

Resonances on Dalitz plot

- E and p conservation imply that if r→ab, then:

  $m_{ab}^2 = m_r^2$
- Resonances show up as bands on Dalitz plot.



Pattern evolves: 1952 - 1964

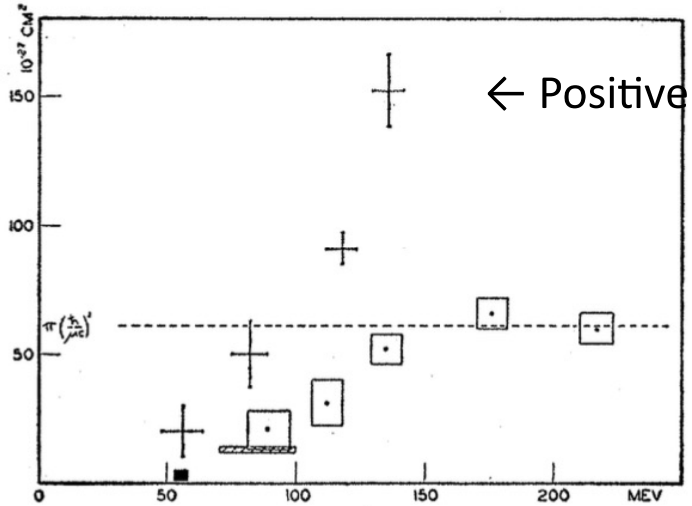
A resonances discovery history

- Hints of resonances
  - The first baryonic resonance $\Delta(1232)$
  - The first strange resonance $\Sigma(1385)$
  - The first meson resonance: K*(890)
- Discovery of $\boldsymbol{\rho}$, $\boldsymbol{\omega}$, $\boldsymbol{\eta}$
- Resonance octets: from Fermi-Yang, Sakata to Gell-Mann (Yuval Ne’eman)
- Discovery of $\boldsymbol{\phi}$
- Further discovery of resonances in decuplet ($J^P=\frac{3}{2}^+$)

The first (baryonic) resonance

Δ (1232)

- The first (**half**) of baryonic resonance shape was discovered by H. Anderson, E. Fermi, E. A. Long, and D. E. Nagle at the Chicago Cyclotron in 1952, by measuring π *p* cross section from an incident pion of 180 MeV on H target.



← Positive pion $\pi^+ p \rightarrow \pi^+ p$

← negative pion

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

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.

- The π+ cross section rose sharply but the data stopped at too low an energy to show conclusively a resonance shape.
- K. A. Brueckner then suggested that a resonance in the π *p* system was being observed

The first (baryonic) resonance

Δ (1232)

- As higher pion energies became available at the Brookhaven Cosmotron, more π p resonances were observed
- Improved measurements of these resonances came from photoproduction experiments carried out at Caltech and at Cornell

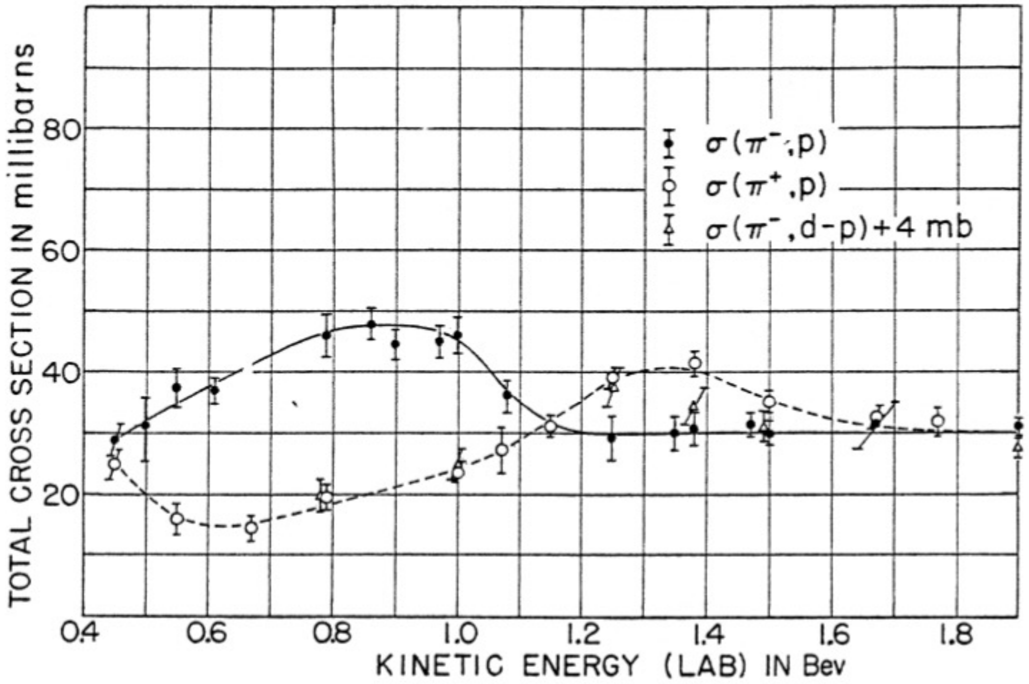
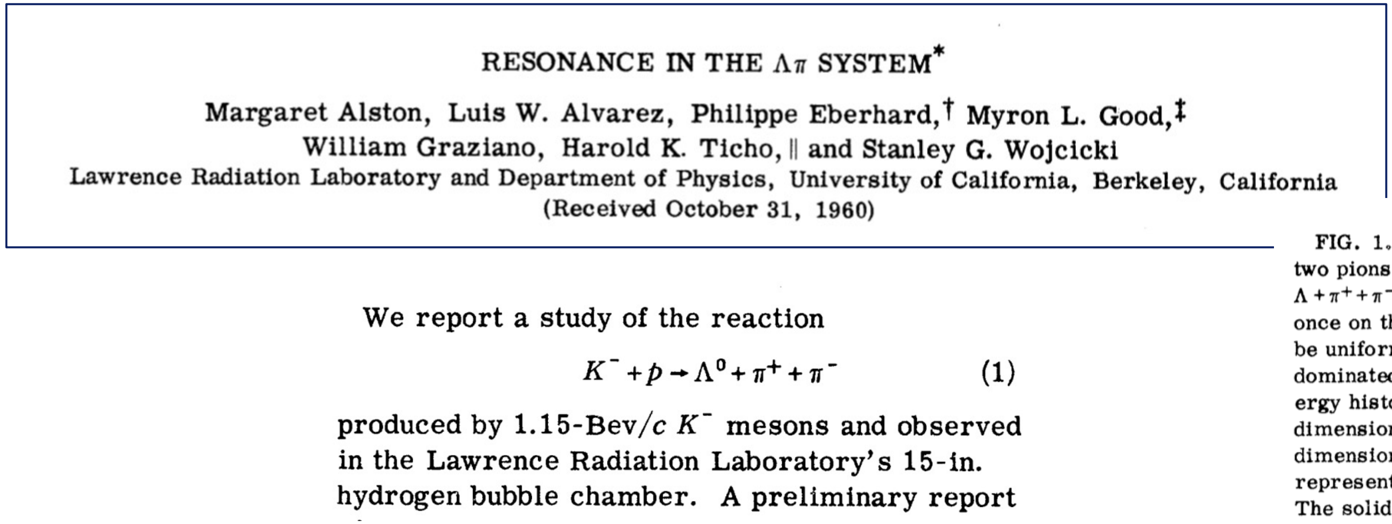


Figure 5.2. Data from the Brookhaven Cosmotron for $\pi^+ p$ and $\pi^- p$ scattering. The cross section peak present for $\pi^- p$ and absent for $\pi^+ p$ demonstrates the existence of an $I = 1/2$ resonance (N^*) near 900 MeV kinetic energy (center-of-mass-energy 1685 MeV). A peak near 1350 MeV kinetic energy (center-of-mass-energy 1925 MeV) is apparent in the $\pi^+ p$ channel, indicating an $I = 3/2$ resonance, as shown in Figure 5.1. Ultimately, several resonances were found in this region. (Ref. 5.3)

The first strange resonance $\Sigma(1385)$

- In 1960 when Luis Alvarez and a team began their work with separated K- beams exposed at the Bevatron. The first resonance observed was the I = 1 $\Lambda\pi$ resonance originally called the Y_1^* - now known as the $\Sigma(1385)$.



RESONANCE IN THE $\Lambda\pi$ SYSTEM*

Margaret Alston, Luis W. Alvarez, Philippe Eberhard,† Myron L. Good,‡
William Graziano, Harold K. Ticho,‖ and Stanley G. Wojcicki
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California
(Received October 31, 1960)

We report a study of the reaction

$$K^- + p \to \Lambda^0 + \pi^+ + \pi^- \qquad (1)$$

produced by 1.15-Bev/c K^- mesons and observed in the Lawrence Radiation Laboratory's 15-in. hydrogen bubble chamber. A preliminary report

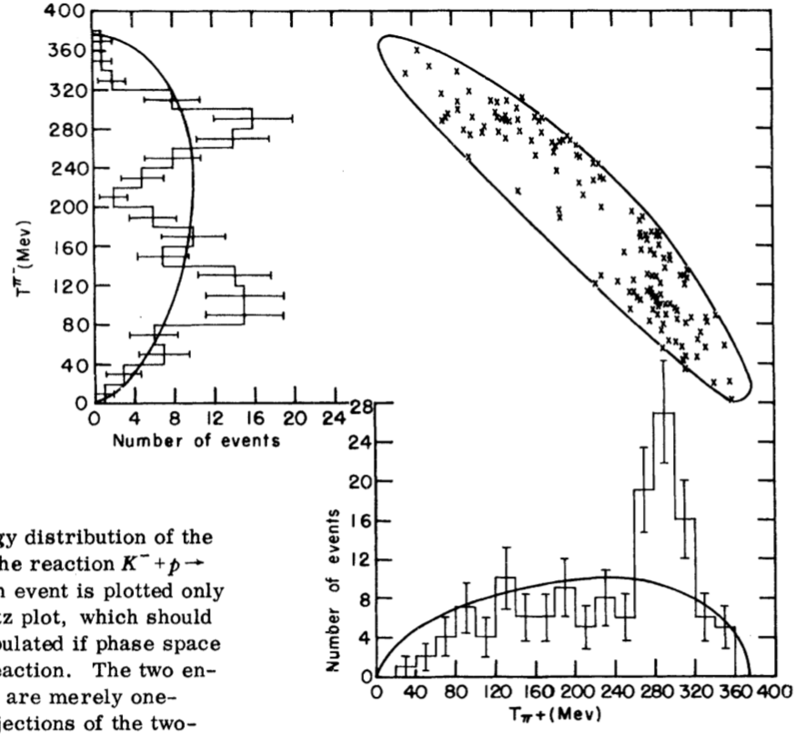
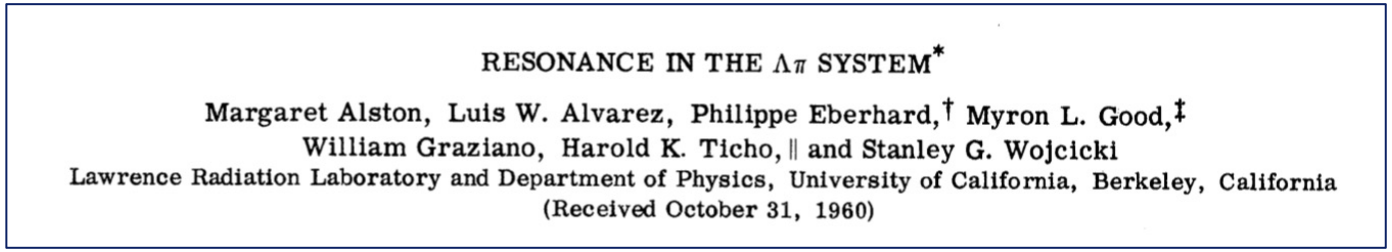


FIG. 1. Energy distribution of the two pions from the reaction $K^- + p \to \Lambda + \pi^+ + \pi^-$. Each event is plotted only once on the Dalitz plot, which should be uniformly populated if phase space dominated the reaction. The two energy histograms are merely one-dimensional projections of the two-dimensional plot, and each event is represented once on each histogram. The solid lines superimposed over the histograms are the phase-space curves.

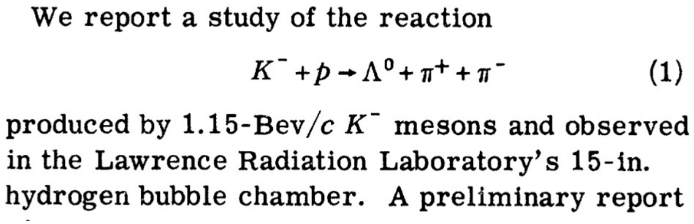
The first strange resonance $\Sigma(1385)$

- In 1960 when Luis Alvarez and a team began their work with separated K- beams exposed at the Bevatron. The first resonance observed was the I = 1 Λπ resonance originally called the Y_1^* - now known as the $\Sigma(1385)$.



RESONANCE IN THE $\Lambda\pi$ SYSTEM*

Margaret Alston, Luis W. Alvarez, Philippe Eberhard,† Myron L. Good,‡
William Graziano, Harold K. Ticho,‖ and Stanley G. Wojcicki
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California
(Received October 31, 1960)



We report a study of the reaction

$$K^- + p \rightarrow \Lambda^0 + \pi^+ + \pi^- \qquad (1)$$

produced by 1.15-Bev/c K^- mesons and observed in the Lawrence Radiation Laboratory's 15-in. hydrogen bubble chamber. A preliminary report

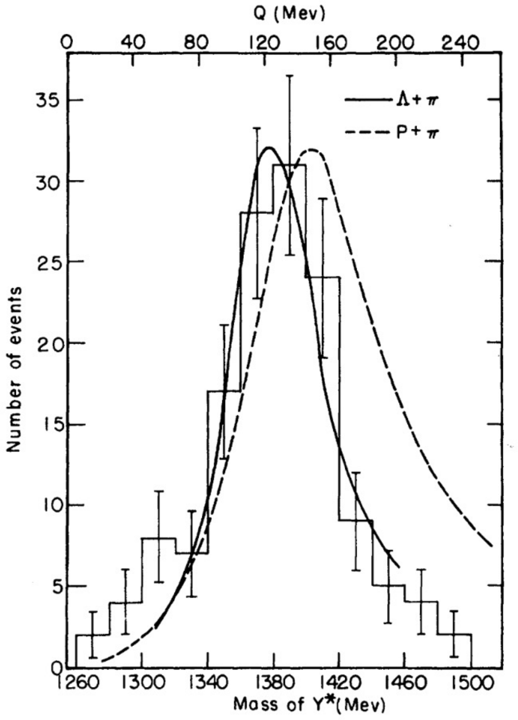
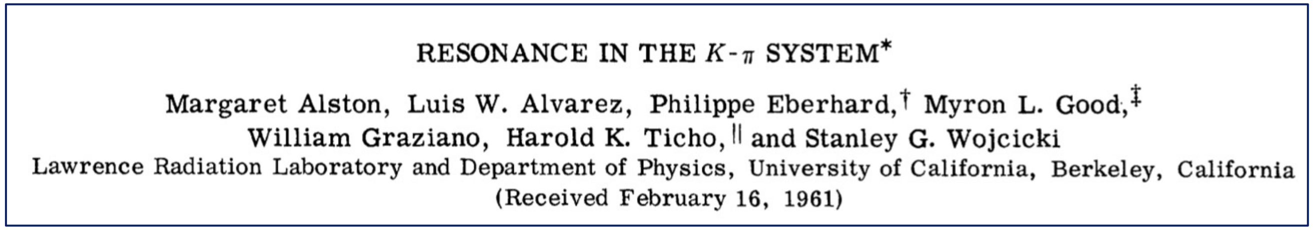


FIG. 2. Mass distribution for Y^* and fitted curves for $\pi\Lambda$ and πp resonances. The lower scale refers only to the $\pi\Lambda$ resonance. Q is the kinetic energy released when either isobar dissociates. The curve for the $\pi\Lambda$ resonances is fitted to the center eight histogram intervals of our data. The πp curve is the fit obtained by Gell-Mann and Watson,[7] to πp scattering data. Both fits are to the formula $\sigma \propto \lambdabar^2 \Gamma^2/[(E-E_0)^2+\frac{1}{4}\Gamma^2]$, where $\Gamma = 2b(a/\lambdabar)^3/[1+(a/\lambdabar)^2]$.

The first meson resonance: K*(890)

- Then, very rapidly, Luis Alvarez and his team used the same 15-in bubble chamber and observed the first meson resonance, K*(890) in $K^- p \to \overline{K}^0 \pi^- p$



RESONANCE IN THE K-π SYSTEM*

Margaret Alston, Luis W. Alvarez, Philippe Eberhard,† Myron L. Good,‡
William Graziano, Harold K. Ticho,|| and Stanley G. Wojcicki
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California
(Received February 16, 1961)

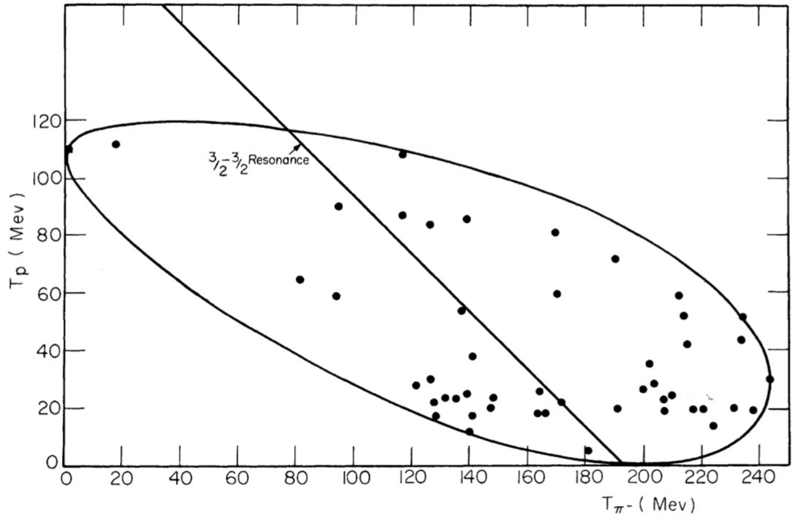


FIG. 1. Phase-space plot of the 48 examples of $K^- + p \to \overline{K}^0 + \pi + p$ reactions.

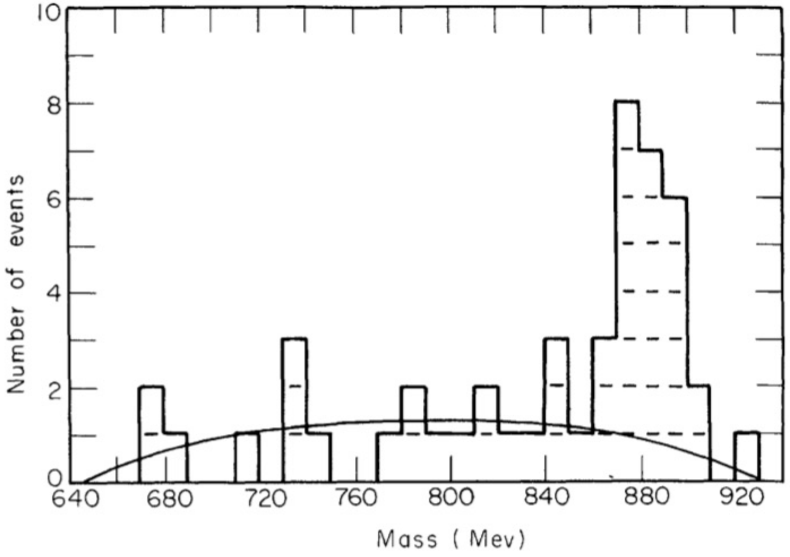
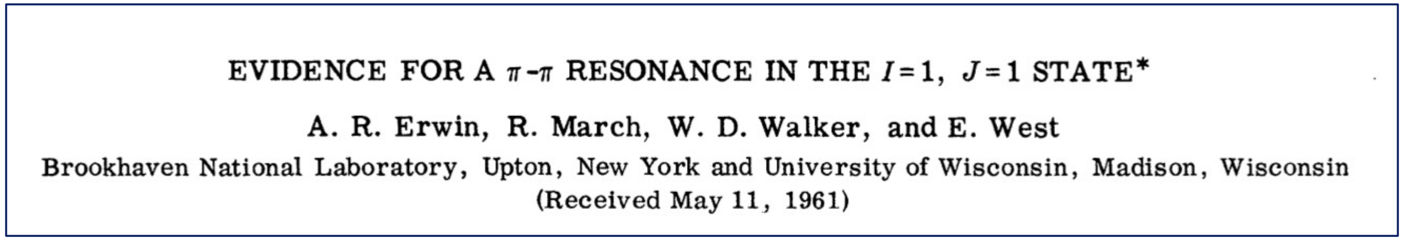


FIG. 2. Mass spectrum of the $\overline{K}^0$ - π^- system. The solid line represents the phase-space curve normalized to background events.

Discovery of ρ

- A very important J = 1 resonance had been predicted first by **Y. Nambu** and later by **W. Frazer** and **J. Fulco**.
- This $\pi\pi$ resonance, the ρ, was observed by **A. R. Erwin** et al. using the proton beam (π^-) and the 14-inch hydrogen bubble chamber at the Cosmotron
- The analysis showed that the ππ scattering near 770 MeV center-of-mass energy was dominated by a spin-1 resonance (The Breit-Wigner formula).



EVIDENCE FOR A π-π RESONANCE IN THE $I=1$, $J=1$ STATE*

A. R. Erwin, R. March, W. D. Walker, and E. West

Brookhaven National Laboratory, Upton, New York and University of Wisconsin, Madison, Wisconsin

(Received May 11, 1961)

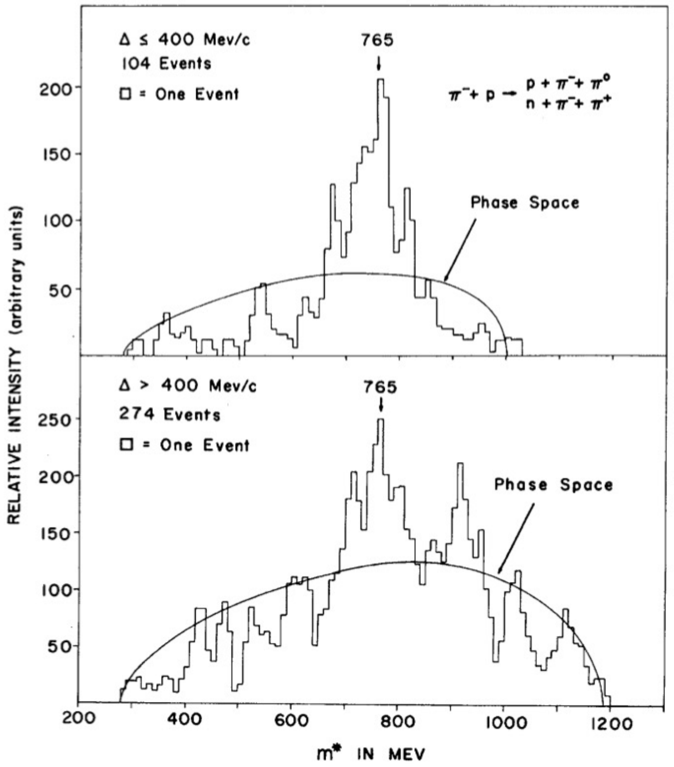
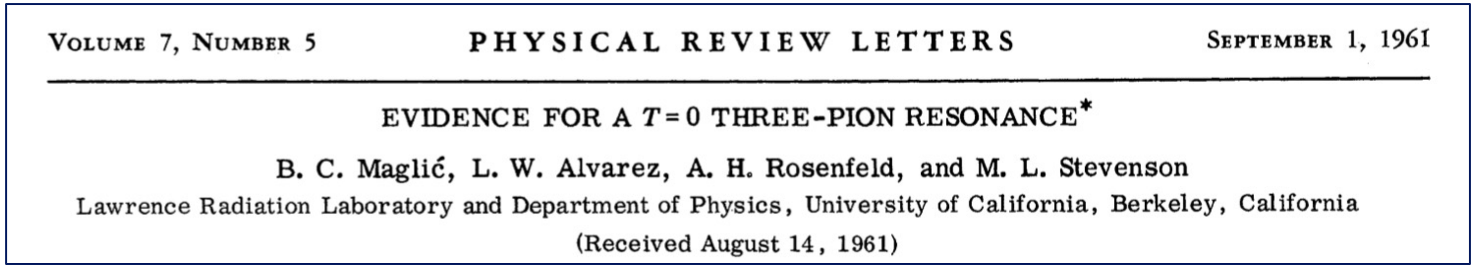


FIG. 2. The combined mass spectrum for the $\pi^-\pi^0$ and $\pi^-\pi^+$ system. The smooth curve is phase space as modified for the included momentum transfer and normalized to the number of events plotted. Events used in the upper distribution are not contained in the lower distribution.

Discovery of ω

- Shortly after the discovery of the ρ, a second vector (spin-1) resonance was found, this time in the I = 0 channel by **B. Maglich**, together with other members of the Alvarez group using 72-in bubble chamber @ LBNL



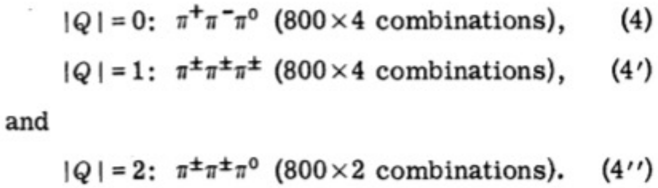
VOLUME 7, NUMBER 5 PHYSICAL REVIEW LETTERS SEPTEMBER 1, 1961

EVIDENCE FOR A $T=0$ THREE-PION RESONANCE*

B. C. Maglić, L. W. Alvarez, A. H. Rosenfeld, and M. L. Stevenson

Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California

(Received August 14, 1961)



$$|Q|=0:\ \pi^+\pi^-\pi^0\ (800\times 4\ \text{combinations}), \qquad (4)$$

$$|Q|=1:\ \pi^\pm\pi^\pm\pi^\pm\ (800\times 4\ \text{combinations}), \qquad (4')$$

and

$$|Q|=2:\ \pi^\pm\pi^\pm\pi^0\ (800\times 2\ \text{combinations}). \qquad (4'')$$

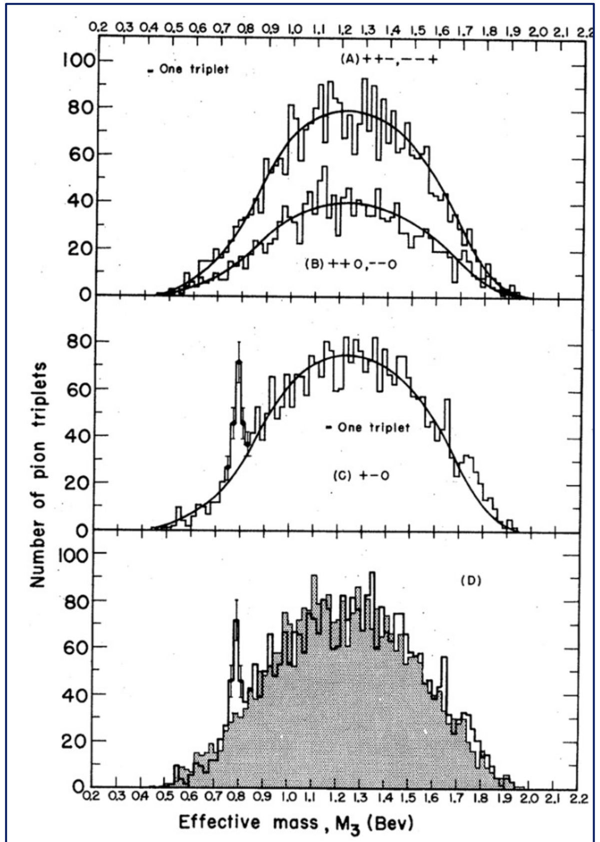


FIG. 1. Number of pion triplets versus effective mass (M_3) of the triplets for reaction $\bar{p}+p\rightarrow 2\pi^+ + 2\pi^- + \pi^0$. (A) is the distribution for the combination (4′), $|Q|=1$; (B) is for the combination (4″), $|Q|=2$; and (C) for (4), $Q=0$, with 3200, 1600, and 3200 triplets, respectively. Full width of one interval is 20 Mev. In (D), the combined distributions (A) and (B) (shaded area) are contrasted with distribution (C) (heavy line).

Discussion: ‘resonance’

- The term “**resonance**” is applied when the produced state decays strongly, as in the $\boldsymbol{\rho}$ or K^*. States such as the Λ, which decay weakly, are termed **particles**.
- The distinction is somewhat artificial. Which states decay weakly and which decay strongly is determined by the masses of the particles involved. The ordering of particles by mass may not be fundamental.
- **Geoffrey Chew** proposed the concept of “**nuclear democracy**”: that all particles and resonances were on an equal footing.

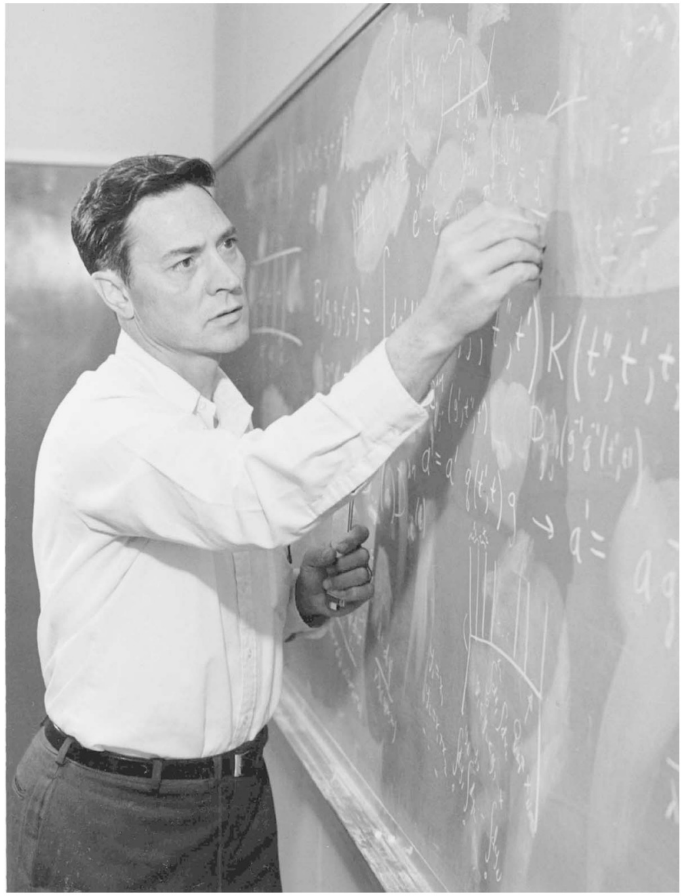


Figure 4. *Geoffrey Chew, circa 1960. Lawrence Berkeley National Laboratory, University of California, Berkeley. Courtesy of the Emilio Segrè Visual Archives, American Institute of Physics.*

Discussion: ‘resonance’

- The proliferation of resonances called for a powerful organizing principle
- **Fermi–Yang model [SU(2)]** to regard **isospin** as the proton and neutron as fundamental objects. The pion can then be thought of as a combination of a nucleon and an antinucleon, for example, $np \rightarrow \pi^+$
- **S. Sakata** [**SU(3)]** proposed to extend Fermi–Yang model by taking the n, p, and Λ as fundamental. In this way the strange mesons could be accommodated: $\Lambda p \rightarrow K^+$
- Ultimately, **Murray Gell-Mann** and independently, **Yuval Ne’eman** proposed a similar but much more successful model

The ‘eightfold’ way

- In the Sakata model the baryons p, n, and Λ formed a 3 of SU(3), while the pseudoscalars formed an **octet**.
- In the version of Gell-Mann and Ne’eman the baryons were in an **octet**, not a triplet. The baryon octet included the isotriplet Σ and the isodoublet Ξ in addition to the nucleons and the Λ. All resonances belong either to octets, or to multiplets that could be made by combining octets.

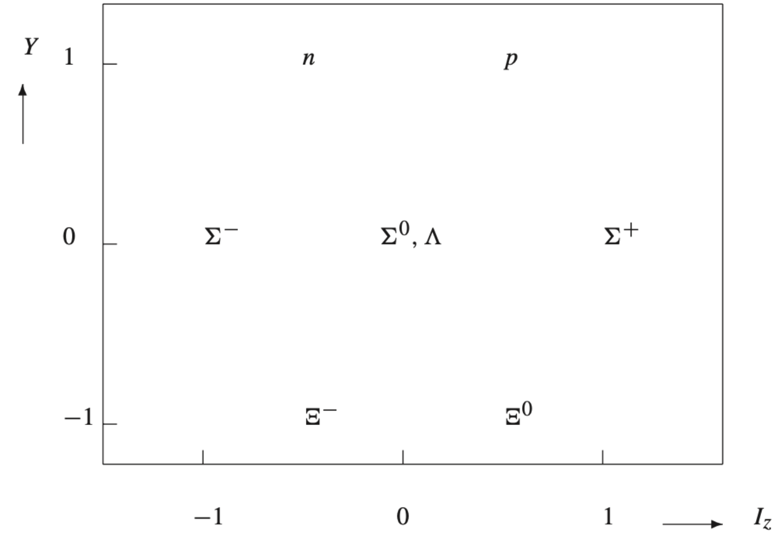


Figure 5.4. The baryon $J^P = 1/2^+$ octet containing the proton and the neutron. The horizontal direction measures I_z, the third component of isospin. The vertical axis measures the hypercharge, $Y = B + S$, the sum of baryon number and strangeness.

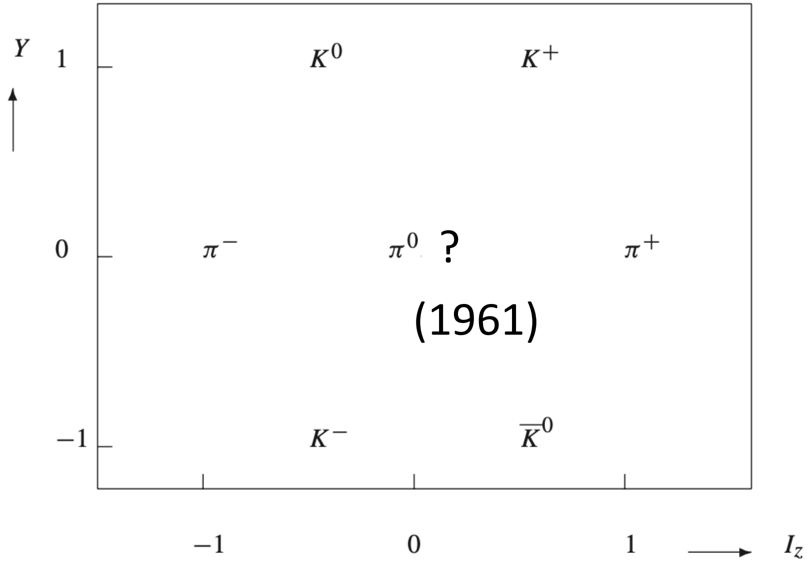
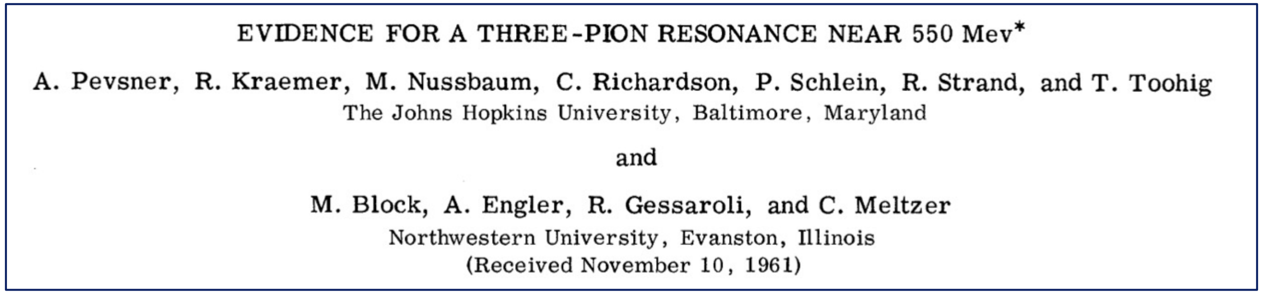


Figure 5.5. The pseudoscalar octet. The horizontal direction measures I_z while the vertical measures the hypercharge, $Y = B + S$.

Discovery of η

- 1961 @ Bevatron (same 72-in bubble chamber forω, Lawrence Berkley)



EVIDENCE FOR A THREE-PION RESONANCE NEAR 550 Mev*

A. Pevsner, R. Kraemer, M. Nussbaum, C. Richardson, P. Schlein, R. Strand, and T. Toohig
The Johns Hopkins University, Baltimore, Maryland

and

M. Block, A. Engler, R. Gessaroli, and C. Meltzer
Northwestern University, Evanston, Illinois
(Received November 10, 1961)

- The η was established as a pseudoscalar later by **M. Chrétien** et al. using a heavy liquid bubble chamber to identify two-photon decay of η

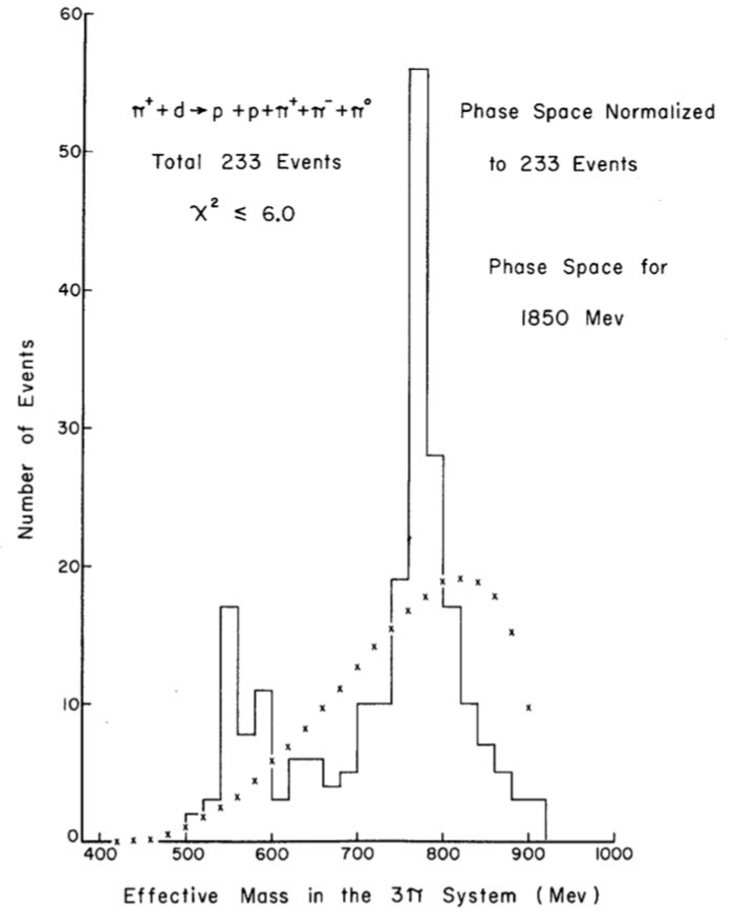
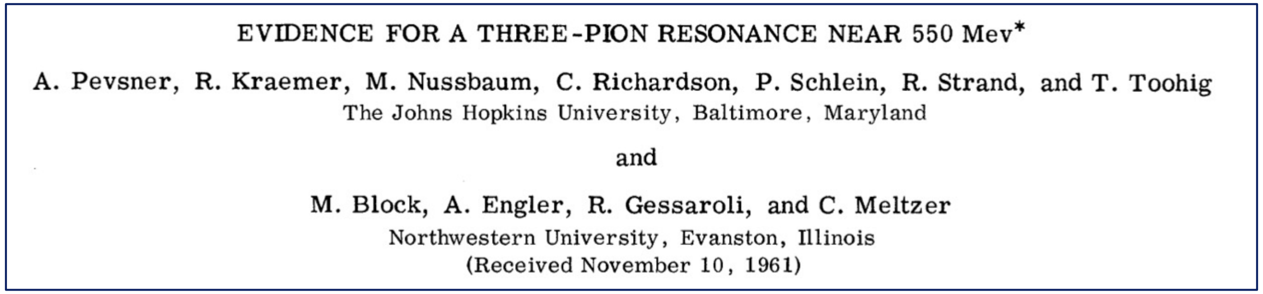


FIG. 2. Histogram of the effective mass of the three-pion system for 233 events.

Discovery of η

- 1961 @ Bevatron (same 72-in bubble chamber forω, Lawrence Berkley)



EVIDENCE FOR A THREE-PION RESONANCE NEAR 550 Mev*

A. Pevsner, R. Kraemer, M. Nussbaum, C. Richardson, P. Schlein, R. Strand, and T. Toohig
The Johns Hopkins University, Baltimore, Maryland

and

M. Block, A. Engler, R. Gessaroli, and C. Meltzer
Northwestern University, Evanston, Illinois
(Received November 10, 1961)

- The η was established as a pseudoscalar later by **M. Chrétien** et al. using a heavy liquid bubble chamber to identify two-photon decay of η

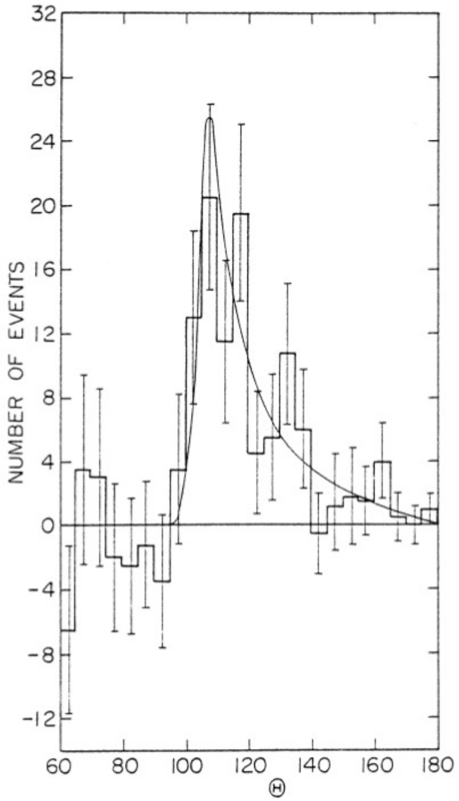


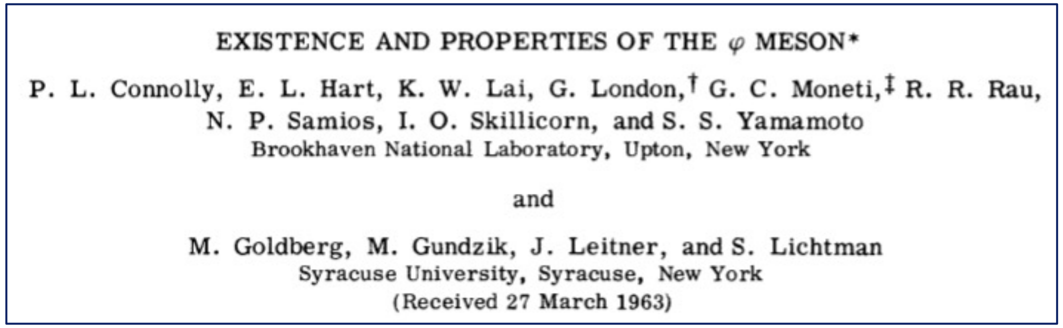
Figure 5.6. A histogram of the opening angle between the two photons in the decay $\eta \to \gamma\gamma$. The solid curve is the theoretical expectation corresponding to the mass of the η (Ref. 5.13).

Discovery of ϕ

$$(1) \qquad K^- p \to \Lambda K^0 \overline{K}^0$$

$$(2) \qquad K^- p \to \Lambda K^+ K^-$$

- An additional vector meson, ϕ, decaying predominantly into KKbar was discovered by two groups, a UCLA team under H. Ticho and a Brookhaven–Syracuse group, P. L. Connolly et al. the former using an exposure of the 72-inch hydrogen bubble chamber at the Bevatron, the latter using the 20-inch hydrogen bubble chamber at the Cosmotron.



EXISTENCE AND PROPERTIES OF THE φ MESON*

P. L. Connolly, E. L. Hart, K. W. Lai, G. London,† G. C. Moneti,‡ R. R. Rau, N. P. Samios, I. O. Skillicorn, and S. S. Yamamoto
Brookhaven National Laboratory, Upton, New York

and

M. Goldberg, M. Gundzik, J. Leitner, and S. Lichtman
Syracuse University, Syracuse, New York
(Received 27 March 1963)

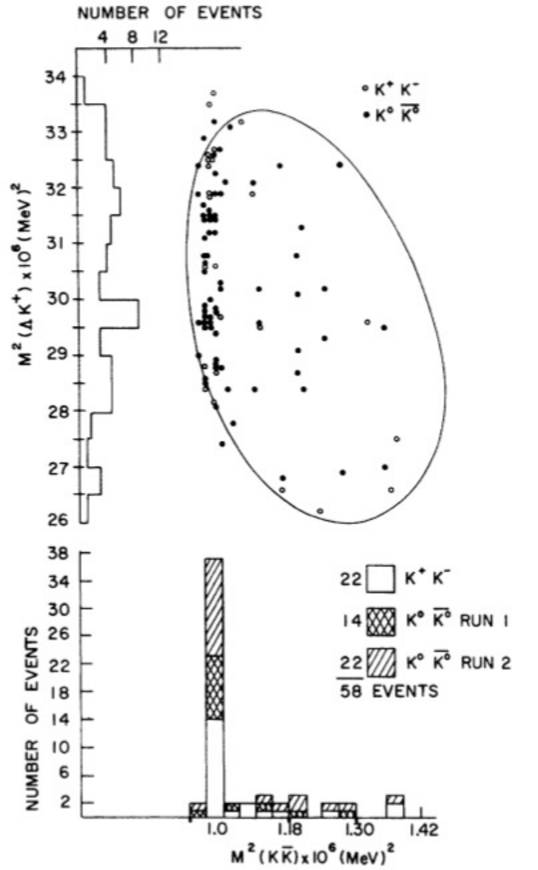
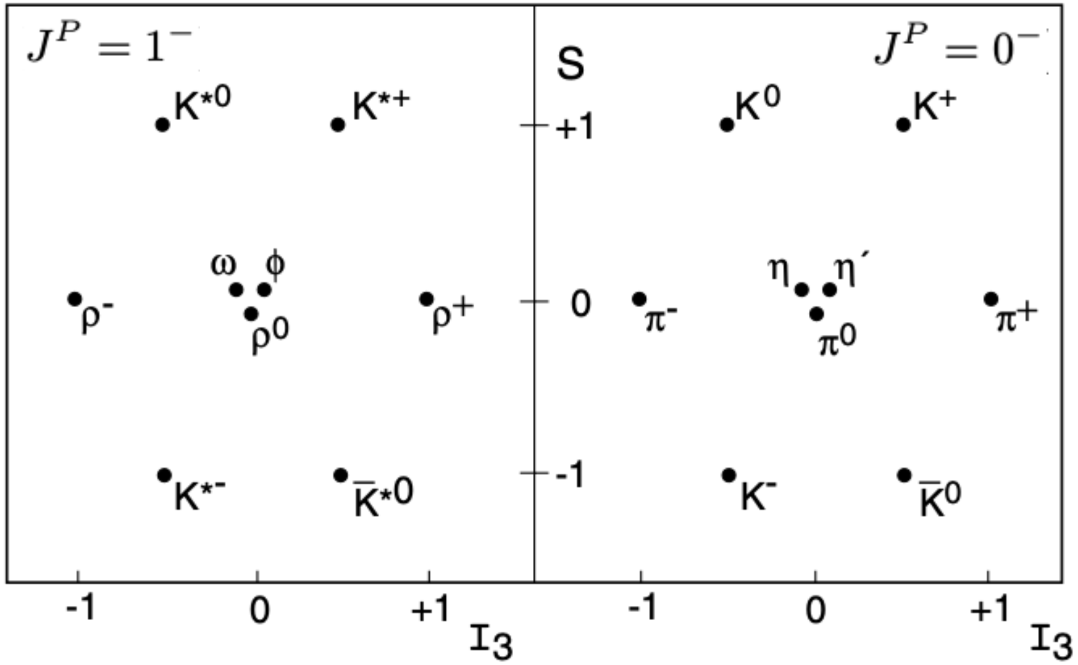


FIG. 1. Dalitz plot for the reaction $K^- + p \to \Lambda + K + \bar{K}$. The effective-mass distribution for $K\bar{K}$ and for ΛK^+ are projected on the abscissa and ordinate (see reference 7).

Discovery of ϕ

- With the addition of the ϕ there were nine vector mesons. This filled an octet multiplet and a singlet (a one-member multiplet).

- Since SU(3) is an approximate rather than an exact symmetry, these states can mix - neither the ω nor the ϕ is completely singlet or completely octet.
- The same situation arises for the pseudoscalars, where there is in addition an η′ meson, which mixes with the η.



More resonances (baryons) in decuplet

- The missing one in the $J^P = (\frac{3}{2})^+$ baryon multiplet (decuplet)

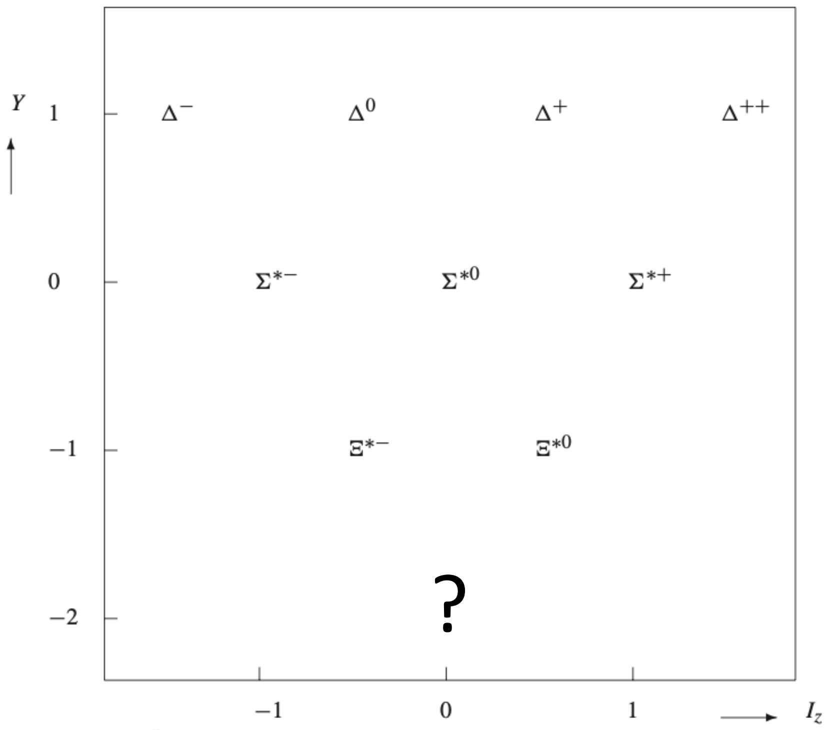


Figure 5.7. The $J^P = 3/2^+$ decuplet completed by the discovery of the Ω^-.

- At the 1962 Rochester Conference, Gell-Mann, declared the multiplet was a 10 and that the tenth member had to be an S=–3, I=0, $J^P = (3/2)^+$ state with a mass of about 1680 MeV

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

$$\Omega^- \rightarrow \Xi^0 \pi^-$$

$$\Xi^0 \rightarrow \Lambda \pi^0$$

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

More resonances (baryons) in decuplet

- The missing one in the $J^P = (\frac{3}{2})^+$ baryon multiplet (decuplet)

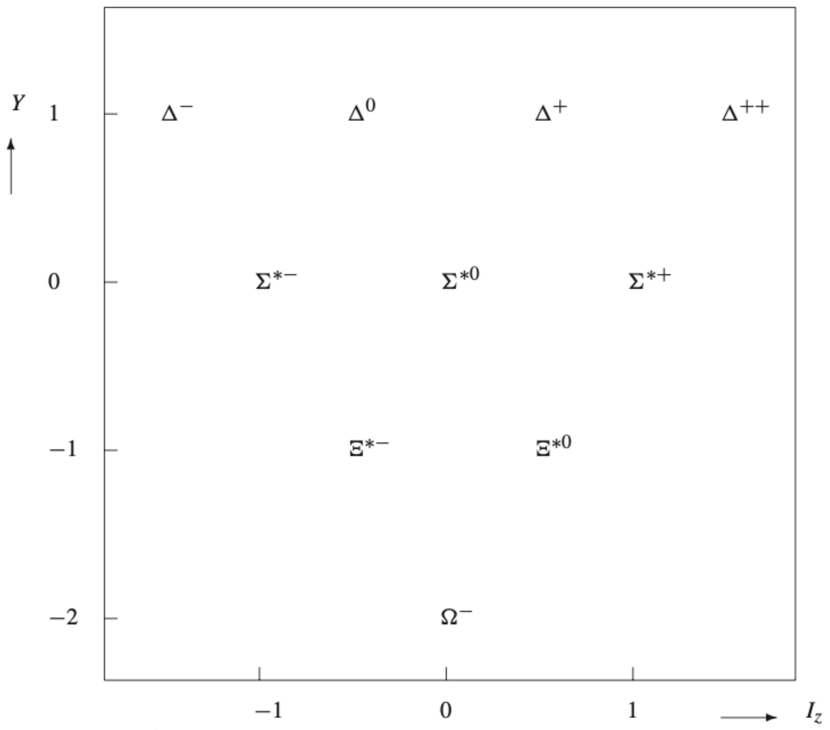
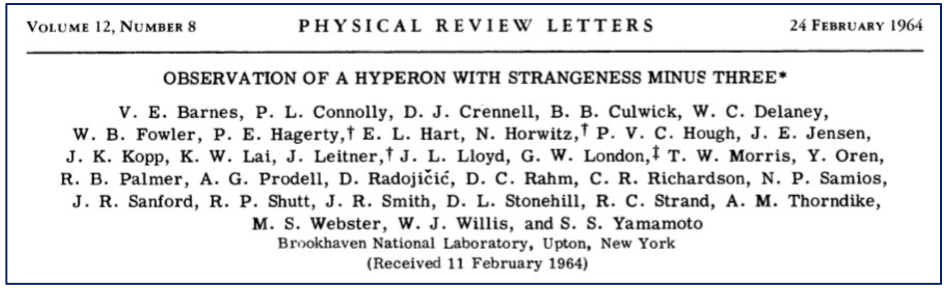


Figure 5.7. The $J^P = 3/2^+$ decuplet completed by the discovery of the Ω^-.

- At the 1962 Rochester Conference, Gell-Mann, declared the multiplet was a 10 and that the tenth member had to be an S=–3, I=0, $J^P = (3/2)^+$ state with a mass of about 1680 MeV (for the 10, it turns out that there should be equal spacing between the multiplets).



VOLUME 12, NUMBER 8 PHYSICAL REVIEW LETTERS 24 FEBRUARY 1964

OBSERVATION OF A HYPERON WITH STRANGENESS MINUS THREE*

V. E. Barnes, P. L. Connolly, D. J. Crennell, B. B. Culwick, W. C. Delaney,
W. B. Fowler, P. E. Hagerty,† E. L. Hart, N. Horwitz,† P. V. C. Hough, J. E. Jensen,
J. K. Kopp, K. W. Lai, J. Leitner,† J. L. Lloyd, G. W. London,‡ T. W. Morris, Y. Oren,
R. B. Palmer, A. G. Prodell, D. Radojičić, D. C. Rahm, C. R. Richardson, N. P. Samios,
J. R. Sanford, R. P. Shutt, J. R. Smith, D. L. Stonehill, R. C. Strand, A. M. Thorndike,
M. S. Webster, W. J. Willis, and S. S. Yamamoto
Brookhaven National Laboratory, Upton, New York
(Received 11 February 1964)

$$K^- p \to \Omega^- K^+ K^0$$

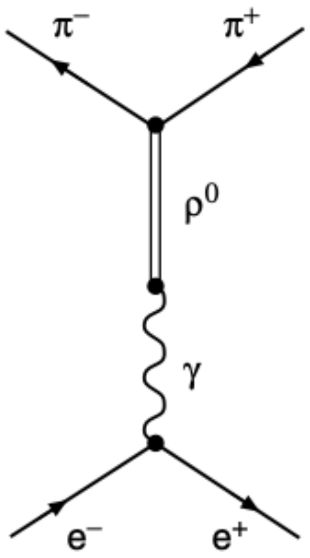
$$\Omega^- \to \Xi^0 \pi^-$$

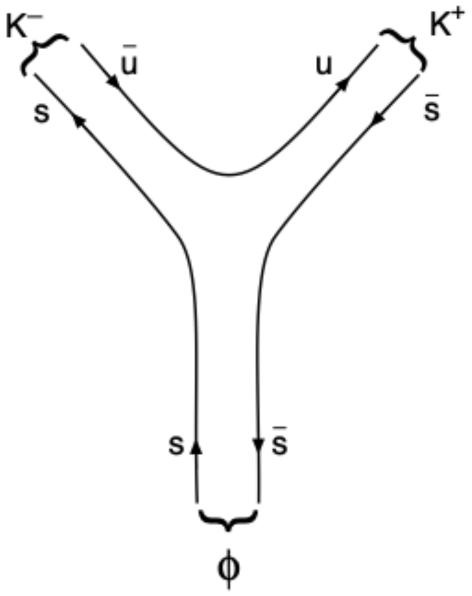
$$\Xi^0 \to \Lambda \pi^0$$

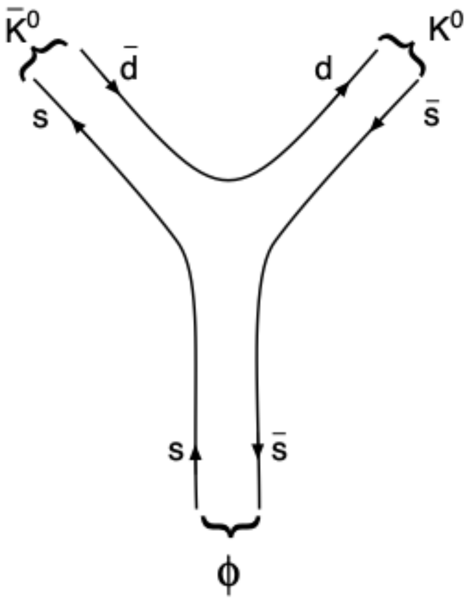
$$\Lambda \to p \pi^-$$

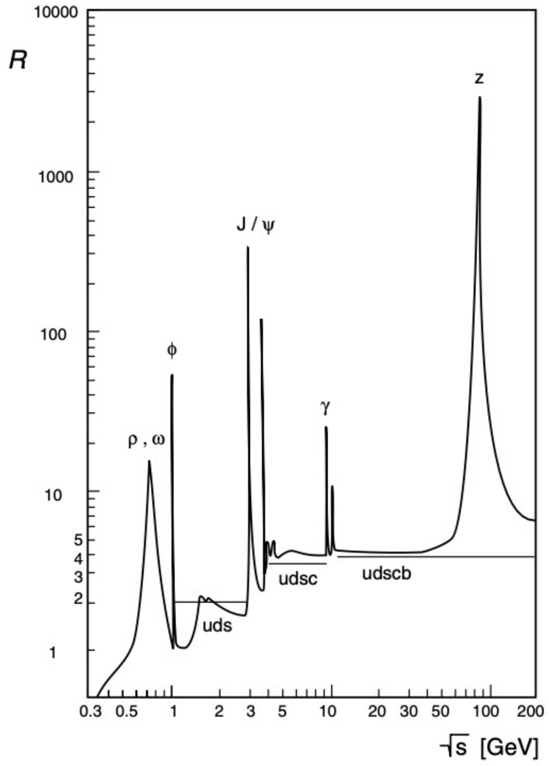
Now, from a modern view…

- Quarks! (Gell-Mann & Zweig from 1963)
- 10^{-25}s → strong interaction









M. Gell-Mann: inventor of quarks

Murray Gell-Mann
(1929–2019)

"In 1963, I chose the name 'quark' for the fundamental constituents of the nucleon. In 1964, the physicist George Zweig also proposed the existence of quarks. I had been reading James Joyce's 'Finnegans Wake,' and a word in the text, 'three quarks for Muster Mark,' sounded like it meant 'three quarks for Mr. Mark.' Since three quarks were needed to make a nucleon, the name seemed appropriate."

M. Gell-Mann: inventor of quarks

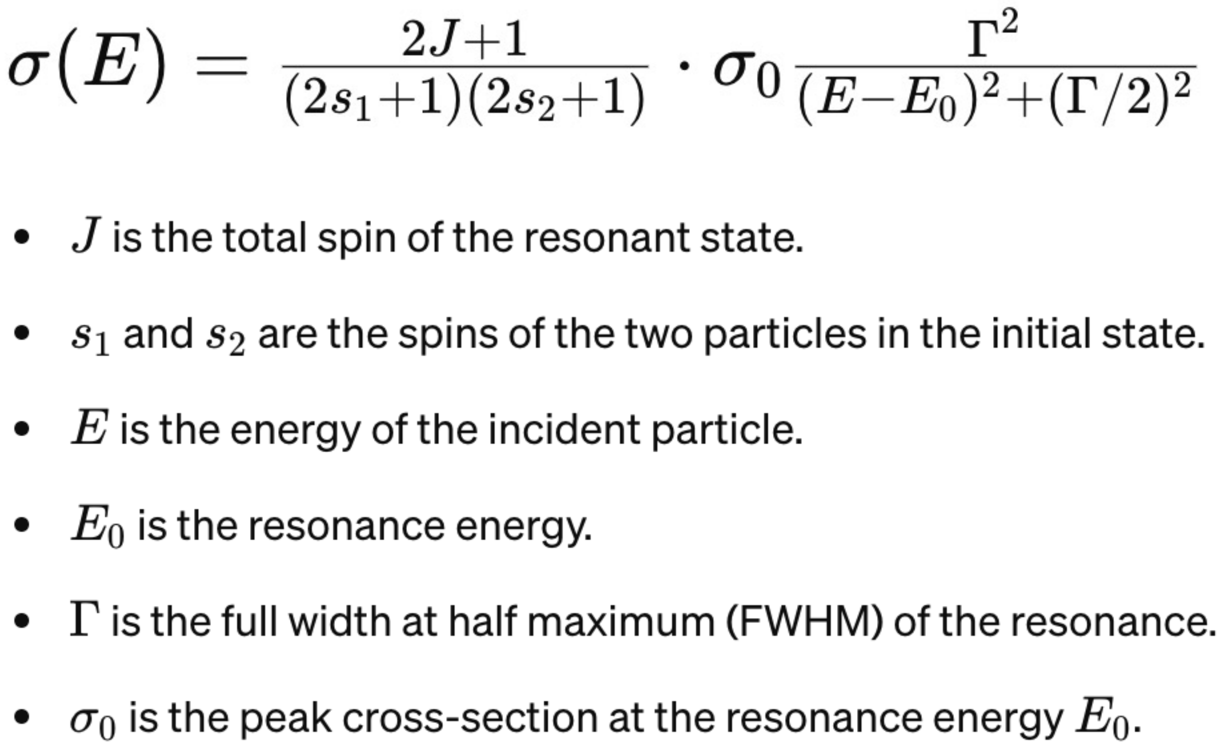

Murray Gell-Mann
(1929–2019)

"What I love about the quark model is that it brought a beautiful simplicity to the understanding of particle interactions. It was as if a complex tapestry suddenly revealed a simple, elegant pattern."

We will see Gell-Mann's genius in the next seminars…

Backup

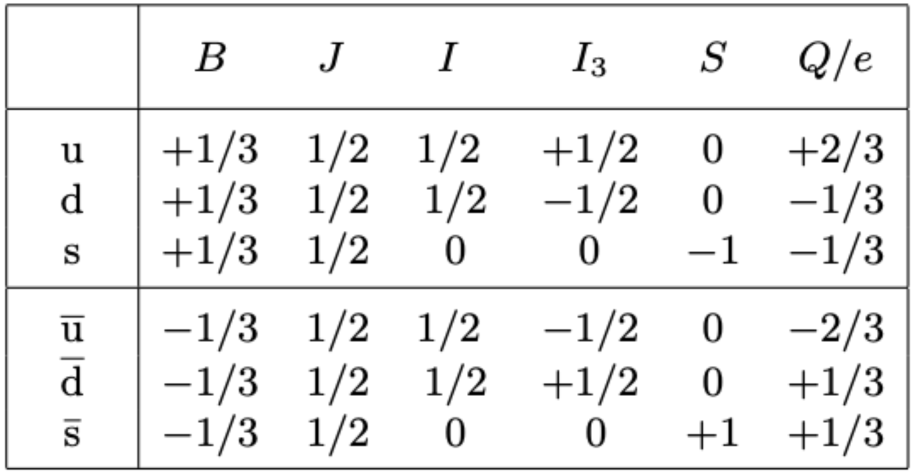
The Breit-Wigner formula



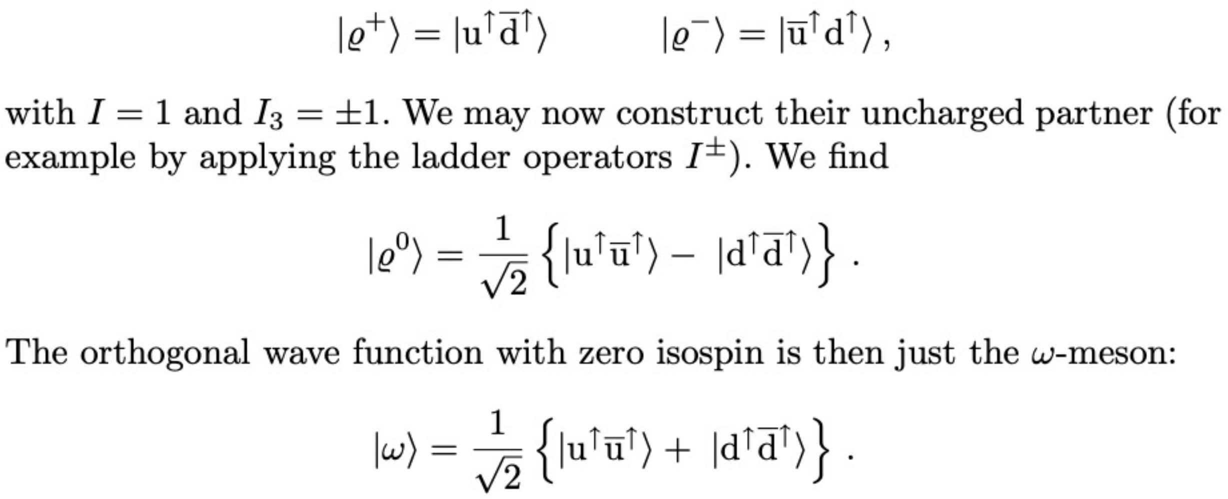
$$\sigma(E) = \frac{2J+1}{(2s_1+1)(2s_2+1)} \cdot \sigma_0 \frac{\Gamma^2}{(E-E_0)^2+(\Gamma/2)^2}$$

- J is the total spin of the resonant state.
- s_1 and s_2 are the spins of the two particles in the initial state.
- E is the energy of the incident particle.
- E_0 is the resonance energy.
- Γ is the full width at half maximum (FWHM) of the resonance.
- σ_0 is the peak cross-section at the resonance energy E_0.

Now, from a much modern view…



	B	J	I	I_3	S	Q/e
u	$+1/3$	$1/2$	$1/2$	$+1/2$	0	$+2/3$
d	$+1/3$	$1/2$	$1/2$	$-1/2$	0	$-1/3$
s	$+1/3$	$1/2$	0	0	-1	$-1/3$
$\bar{\mathrm{u}}$	$-1/3$	$1/2$	$1/2$	$-1/2$	0	$-2/3$
$\bar{\mathrm{d}}$	$-1/3$	$1/2$	$1/2$	$+1/2$	0	$+1/3$
$\bar{\mathrm{s}}$	$-1/3$	$1/2$	0	0	$+1$	$+1/3$



$$|\varrho^+\rangle = |\mathrm{u}^\uparrow \bar{\mathrm{d}}^\uparrow\rangle \qquad |\varrho^-\rangle = |\bar{\mathrm{u}}^\uparrow \mathrm{d}^\uparrow\rangle\,,$$

with $I = 1$ and $I_3 = \pm 1$. We may now construct their uncharged partner (for example by applying the ladder operators $I^\pm$). We find

$$|\varrho^0\rangle = \frac{1}{\sqrt{2}}\left\{|\mathrm{u}^\uparrow \bar{\mathrm{u}}^\uparrow\rangle - |\mathrm{d}^\uparrow \bar{\mathrm{d}}^\uparrow\rangle\right\}\,.$$

The orthogonal wave function with zero isospin is then just the ω-meson:

$$|\omega\rangle = \frac{1}{\sqrt{2}}\left\{|\mathrm{u}^\uparrow \bar{\mathrm{u}}^\uparrow\rangle + |\mathrm{d}^\uparrow \bar{\mathrm{d}}^\uparrow\rangle\right\}\,.$$

Now, from a much modern view…

- 10^{-25}s → strong interaction → quark-antiquark states in the e+e- collider.
- Vector mesons (J=1 and negative parity)
- 770 – 780 MeV: interference of two resonances (mixed states of u- and d-quarks)

$$\varrho^0 \rightarrow \pi^+\pi^- \,,$$
$$\omega \rightarrow \pi^+\pi^0\pi^-$$

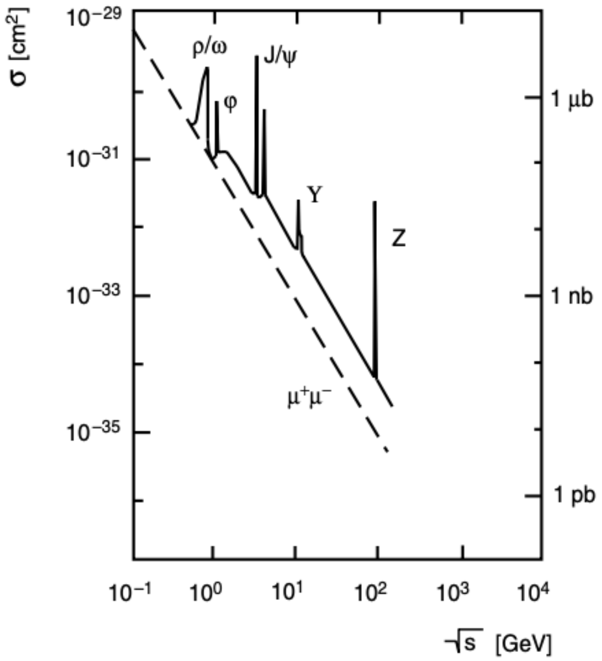
- 1019 MeV:

$$\phi \rightarrow \mathrm{K}^+ + \mathrm{K}^- \,,$$
$$\phi \rightarrow \mathrm{K}^0 + \overline{\mathrm{K}}^0 \,.$$

Pattern evolves: 1952 - 1961

Background & introduction

- Resonance? Particles?
  - Cross-section depends on the width
  - Fixed mass and well-defined quantum numbers J^P
  - Therefore resonable to call them particles



From particles to resonances

- Particles ($\tau = 10^{-10}$s) → therefore a visible distance in a bubble chamber or emulsion before decaying
- Today's talk (1952 – 1961): we entered an era of spotting resonances **in the view of patterns** → deeper level of particles → quarks
  - Particle accelerators and scattering cross-sections
  - E width (10 – 200 MeV) → $\tau = \hbar$/100 MeV $\approx 10^{-25}$s

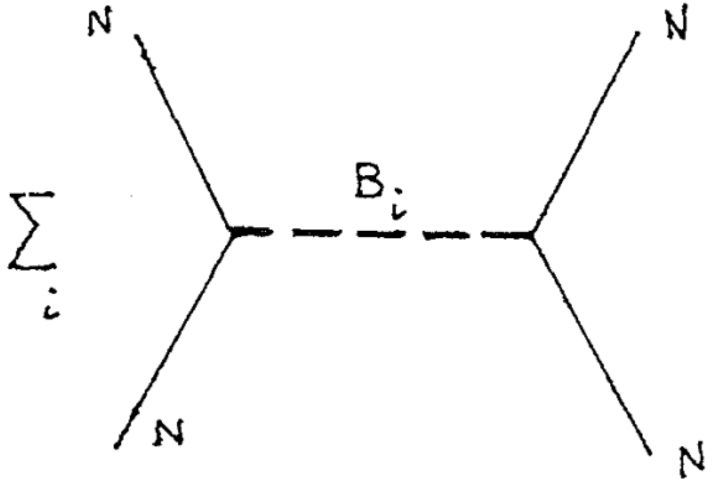
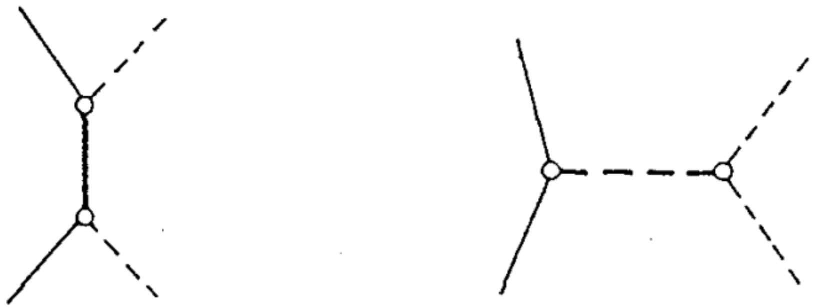


Fig. 1.



(a) (b)

Fig. 9. The types of diagram contributing to pion-nucleon scattering. The broken line denotes the pion and the bold line denotes the fermion which includes the nucleon.

Fig. 2. Taken from S. Sawada et al., Prog. Theor. Phys. **28** (1962), 991.

Properties (G-parity, etc)