Elementary Particles I

3 – Strong Interaction

Resonances, Isospin, Strangeness, Unitary Symmetries

Strong Interaction

Originally pictured as an attractive force between nucleons, required to overcome repulsive Coulomb interaction between protons in nuclei

Main features:

Strength
Short range
Charge independence

Several, rather complicated features (repulsive core, many body effects,…)
For a long time, difficult to understand: lot of guesswork, many models

Today, believed to be a *residual force* between ‘color neutral’ particles (*hadrons*), a remnant of color interaction between colored quarks and gluons

Somewhat similar to Van der Waals/Covalent bond between ‘neutral’ molecules, coming from electromagnetic interaction between charged electrons and nuclei

Yukawa Theory

First attempt to model strong interaction after the electromagnetic:
Exchange of mediator particles $\rightarrow$ Prediction of *pion*

Mass > 0	Limited range
Spin $\neq 1$	Vector particle would yield repulsive forces between identical particle
Charged,Neutral	Same force for $pp,\ nn,\ pn$

Electromagnetism

$\frac{\partial^2 \varphi}{\partial t^2} - \nabla^2 \varphi = -\rho$ Wave equation - Scalar potential

$\nabla^2 \varphi = \rho$ Static case

$\rho_G(\mathbf{r}) = e\delta(\mathbf{r})$ Point source at the origin

$\rightarrow \varphi_G(\mathbf{r}) = \frac{e}{r}$ Green's function $\equiv$ Coulomb potential

Yukawa

$\frac{\partial^2 \varphi}{\partial t^2} - \nabla^2 \varphi - m^2 = -\rho$ Wave equation - Pion field

$\nabla^2 \varphi + m^2 = \rho$ Static case

$\rho_G(\mathbf{r}) = g\delta(\mathbf{r})$ Point source at the origin

$\rightarrow \varphi_G(\mathbf{r}) = \frac{g\ e^{-mr}}{r}$ Green's function $\equiv$ Yukawa potential

Pions

Discovered after the II World War (Cosmic Rays, Accelerators)
Properties

Mass	135 MeV	Neutral
	139 MeV	Charged
Spin	0	
Parity	-	
Charge parity	+	
Lifetime	$25\ 10^{-9}$ s	Charged
	10^{-16} s	Neutral
Decay modes (Dominant)	$\mu\nu$	Charged
	$\gamma\gamma$	Neutral

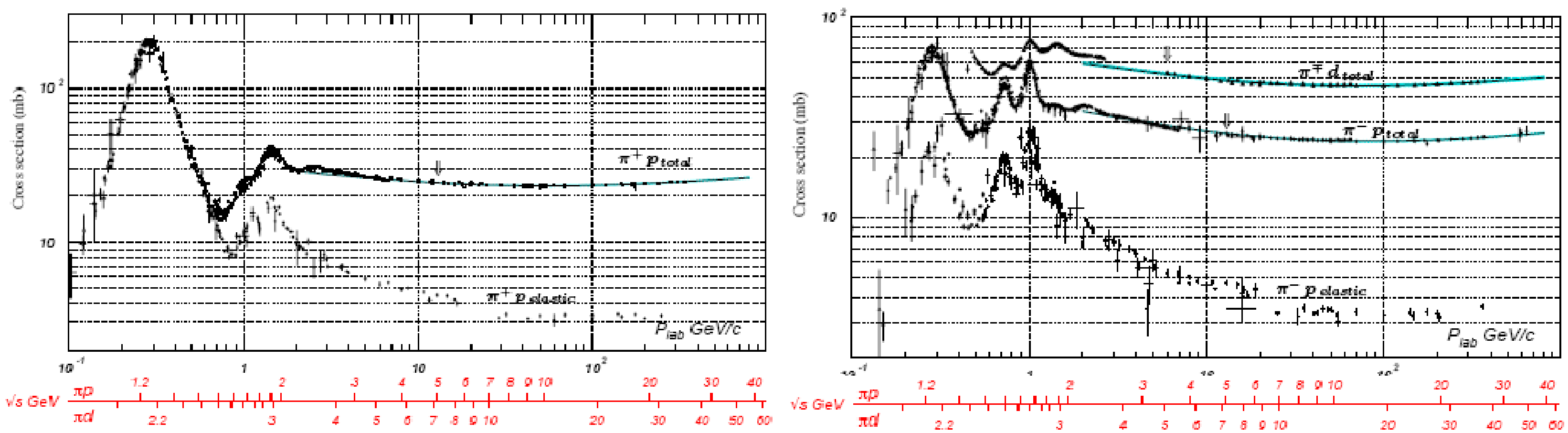
Stable vs. strong decays, as the *lightest hadron*
Copiously produced at first accelerators (synchrocylotrons)
Charged pions easily focused into collimated, high energy beams

Scattering

As for electromagnetic, strong interaction can be investigated by scattering experiments
Perform experiments like

$$p+p, \quad p+n, \quad \pi^{\pm}+p, \quad \pi^{\pm}+n$$

Pion: Spinless $\rightarrow$ Understanding πN scattering easier than NN

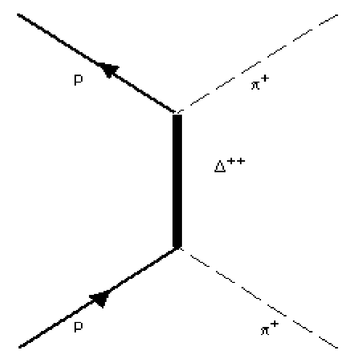


Total cross section plots - Observe lot of structure

Δ-Resonance: Formation

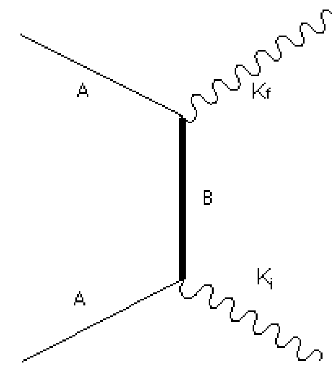
First observed by Fermi and collaborators in πN scattering (1951)

$$\pi^+ + p \to \Delta^{++} \to \pi^+ + p$$



With some caveats, can be considered as a kind of excited nucleon state (But: Different spin, quark content)

Also observed in other charge states Δ^+, Δ^-, Δ^0 and in many different processes (strong, e.m. and weak)



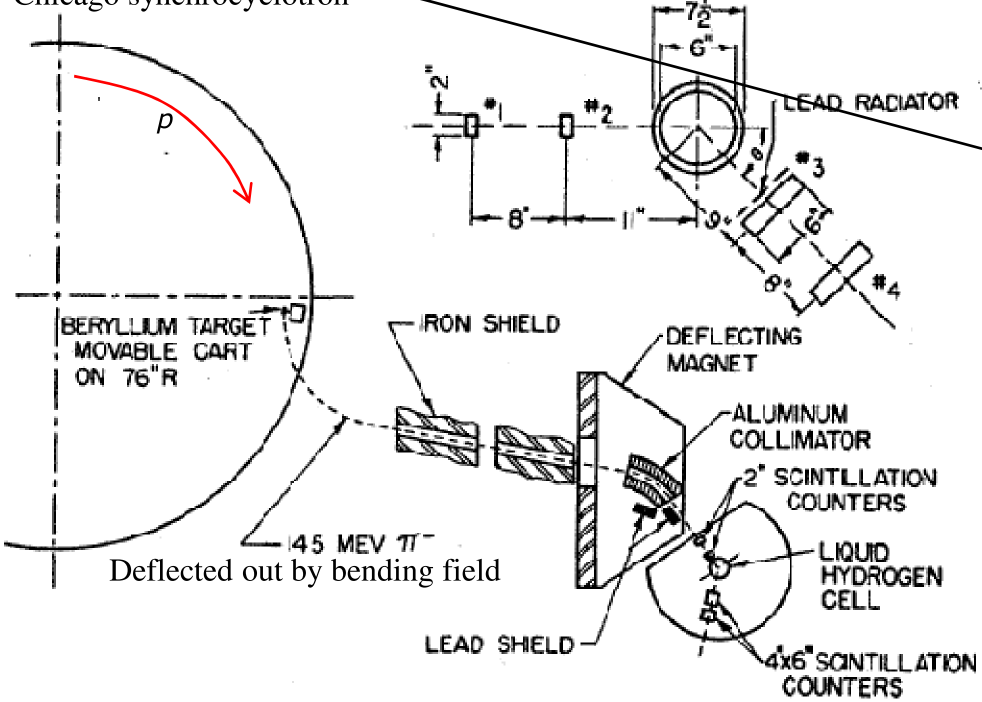
Some analogy with photon excitation of atomic levels

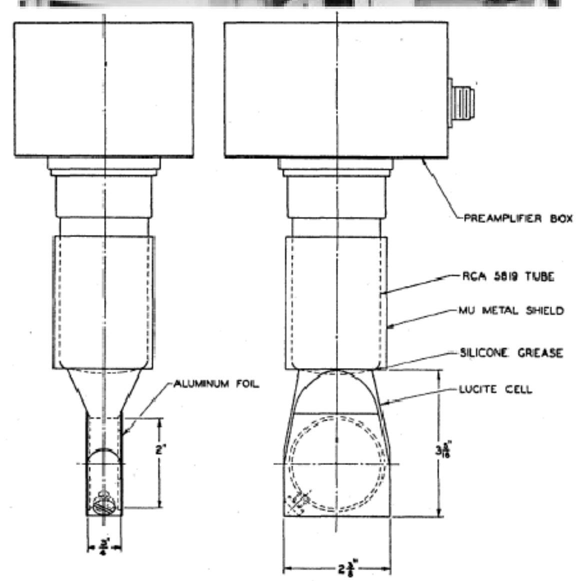
$\gamma + A \to B \to \gamma + A$, A ground state, B excited level

Good indication that the nucleon is a *composite* object

Discovery of Δ - 1951

Chicago synchrocyclotron





Plastic scintillators

Collect first data on 2-body reactions:

$$\pi^+ + p \to \pi^+ + p$$

$$\pi^- + p \to \pi^- + p$$

$$\pi^- + p \to \pi^0 + n$$

Δ^{++} Resonance

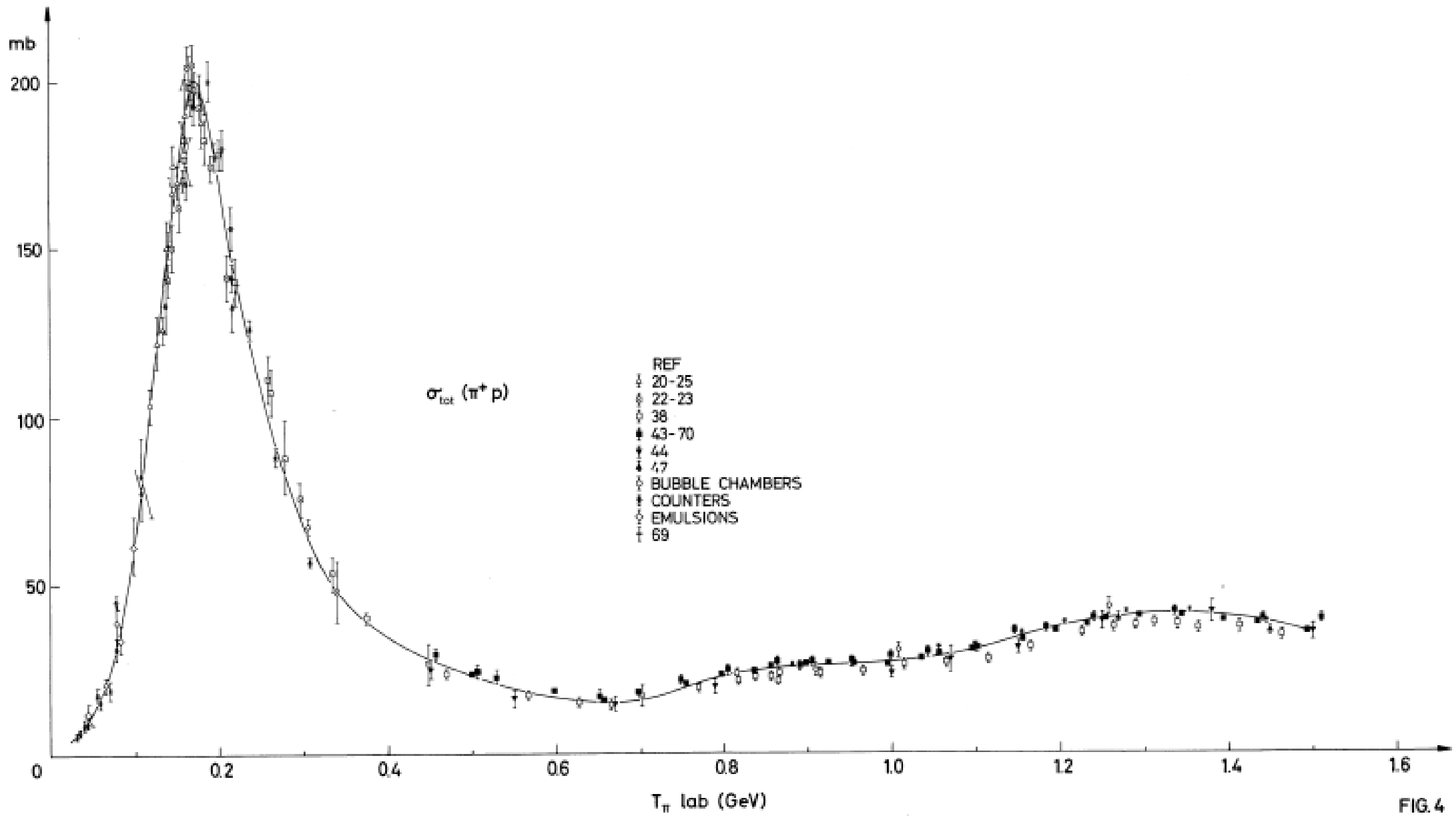


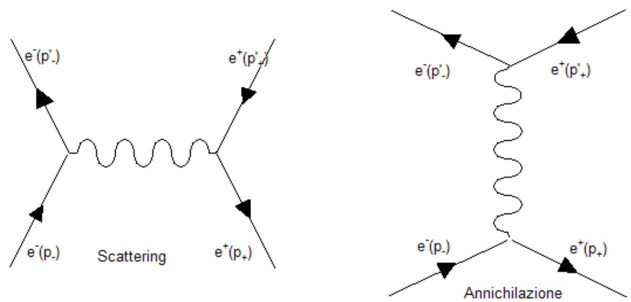
FIG. 4

Propagators

Take first a QED example: Bhabha scattering at $\sqrt{s} \ll M_{Z^0}$

$$e^- + e^+ \rightarrow e^- + e^+$$

Two one-photon diagrams



t-channel *s*-channel

t-channel: Virtual photon has $q^2 < 0$ space-like

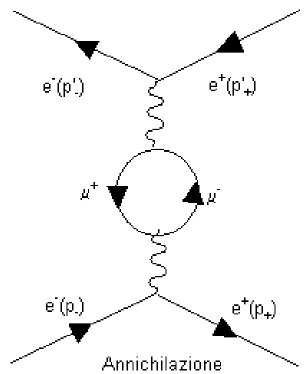
s-channel: Virtual photon has $q^2 > 0$ time-like

In both cases : Virtual photon propagator $= \dfrac{1}{q^2}$

Propagators in the *s*-channel - I

Taking radiative corrections to one loop:

$$\text{Virtual photon propagator} = \frac{1}{q^2\left(1-\overline{\Pi}_{\gamma}^{(2)}\left(q^2\right)\right)}$$



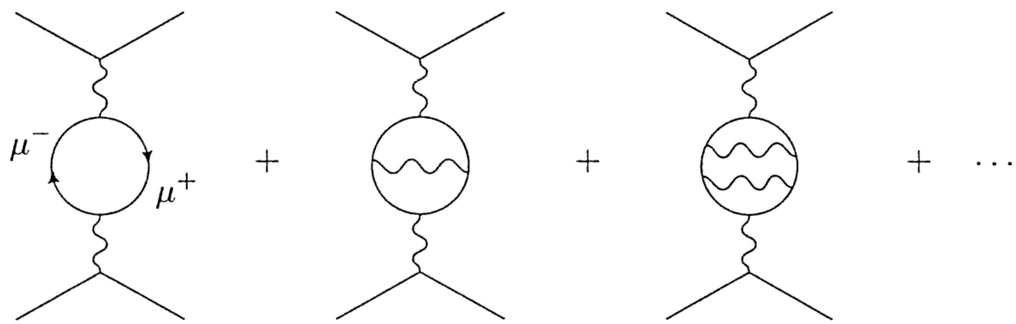
Correction resulting from fermion e.m. currents circulating in the loop, after renormalization
In principle: All fermion loops, leptons & quarks, should be included

$q^2 > 4m_f^2 \rightarrow \overline{\Pi}_{\gamma}^{(2)}\left(q^2\right)$ becomes *complex*

Nonzero amplitude for the virtual photon to materialize as a $f\,\overline{f}$ pair *on-shell*

Propagators in the *s*-channel - II

Among all fermion circulating in the loop, take a muon pair
Taking further perturbative expansion :



Higher order diagrams: Usually negligible

When $\sqrt{s} = E_{CM} \sim M_{bound} \equiv M$, Coulomb attractive force between muons very strong
→ Higher order diagrams large

Naive understanding:

A $\mu^+\mu^-$ pair has bound states, like a hydrogen atom
When $E_{CM} \approx M$: large amplitude for the scattering process to yield a $\mu^+\mu^-$ bound state

Propagators in the *s*-channel - III

Imaginary part tied to bound state being *unstable*:
Unlike the *H* atom, muonic atom annihilates into various channels

$$q^2 \sim M^2 \quad \to \overline{\Pi}_\gamma^{(2)}\left(q^2\right) \approx \frac{M^2 - iM\Gamma}{q^2}$$

$$\to \frac{1}{q^2\left(1-\overline{\Pi}_\gamma^{(2)}\left(q^2\right)\right)} \approx \frac{1}{q^2 - M^2 + iM\Gamma}$$ Propagator of a massive, unstable particle

$$q^2 = s = E_{CM}^2 \quad \to \frac{1}{q^2\left(1-\overline{\Pi}_\gamma^{(2)}\left(q^2\right)\right)} \approx \frac{1}{q^2 - M\left(M - i\Gamma\right)} = \frac{1}{E_{CM}^2 - M^2 + iM\Gamma}$$

$$\to \frac{1}{q^2\left(1-\overline{\Pi}_\gamma^{(2)}\left(q^2\right)\right)} \approx \frac{1}{\left(E_{CM} - M\right)\underbrace{\left(E_{CM} + M\right)}_{\approx 2M} + iM\Gamma}$$

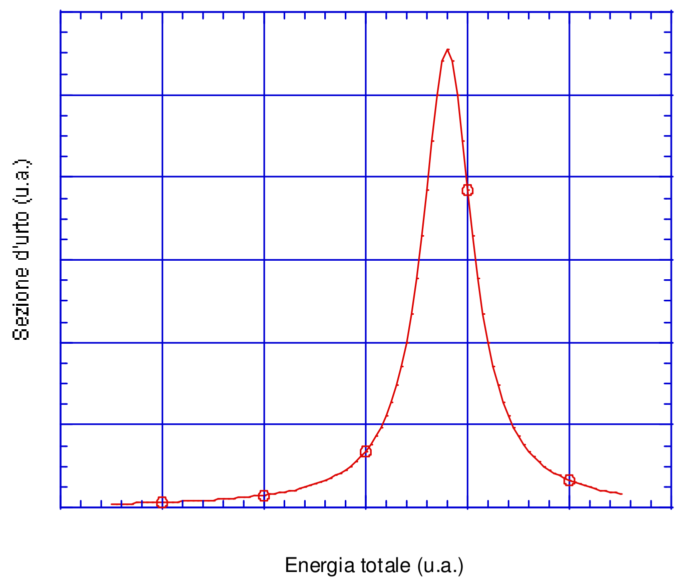
$$\to \frac{1}{q^2\left(1-\overline{\Pi}_\gamma^{(2)}\left(q^2\right)\right)} \approx \frac{1}{2M}\frac{1}{\left(E_{CM} - M\right) + i\Gamma/2}$$

Total cross section: Strongly peaked at $E_{CM} \approx M$

Propagators in the *s*-channel - IV

General rule:

Every time the intermediate state is coupled to an unstable state (excited bound state, genuine elementary particle coupled to decay channels, …), the s-channel propagator and cross section show resonant behavior when the total energy is close to the mass of the unstable state



Potential Scattering

Attempts to understand strong interaction

Formalism of potential scattering:
Not a proper tool to describe relativistic regime (particle creation/destruction)
$\rightarrow$ Go for Field Theory

Nevertheless:
Believed to be somewhat useful to get insight into simplest (2-body) reactions, like elastic scattering

Phase shifts analysis:
Try to reconstruct the strong interaction structure from scattering data

Observe:

Past: Lot of work spent in the attempt of modeling 'simplest' reactions (e.g. Mandelstam representation, Regge poles, …)
Now: The 'simplest' reactions finally understood to be quite complicated, much more than anticipated ($\leftarrow$ Non perturbative interaction regime)

Resonances - I

Partial waves expansion

$$d\sigma = v\frac{|f|^2}{v}d\Omega = |f|^2\,d\Omega \rightarrow \frac{d\sigma}{d\Omega} = |f|^2$$

Scattering amplitude:

$$f(\theta) = \tfrac{1}{2ik}\sum_{l=0}^{\infty}(2l+1)\left(e^{2i\delta_l}-1\right)P_l(\cos\theta) = \tfrac{1}{k}\sum_{l=0}^{\infty}(2l+1)\frac{e^{2i\delta_l}-1}{2i}P_l(\cos\theta)$$

$$f_l = \frac{e^{2i\delta_l}-1}{2i} = e^{i\delta_l}\,\frac{e^{i\delta_l}-e^{-i\delta_l}}{2i} = e^{i\delta_l}\sin\delta_l$$

$$\rightarrow \frac{1}{f_l} = \frac{1}{\sin\delta_l}e^{-i\delta_l} = \frac{1}{\sin\delta_l}\left(\cos\delta_l - i\sin\delta_l\right) = \cot\delta_l - i$$

$$\rightarrow f_l = \frac{1}{\cot\delta_l - i}$$

$$\cot\delta_l\Big|_{\delta_l=\frac{\pi}{2}} = 0 - \frac{1}{\sin^2\delta_l}\Bigg|_{\delta_l=\frac{\pi}{2}}\left(\delta_l - \frac{\pi}{2}\right) + \ldots \approx -\left(\delta_l - \frac{\pi}{2}\right)$$

Resonances - II

For E_R such that $\delta_l(E_R)=\dfrac{\pi}{2}$, expand into power series around E_R :

$$\delta_l(E)=\delta_l(E_R)+\left.\frac{d\delta_l}{dE}\right|_{E=E_R}(E-E_R)+\dots,\quad \frac{2}{\Gamma}\equiv\left.\frac{d\delta_l}{dE}\right|_{E=E_R}\rightarrow\delta_l\approx\frac{\pi}{2}+\frac{E-E_R}{\Gamma/2}$$

$$\rightarrow\cot\delta_l\underset{E\sim E_R}{\approx}-\left(\delta_l-\frac{\pi}{2}\right)=-\left(\frac{\pi}{2}+\frac{E-E_R}{\Gamma/2}-\frac{\pi}{2}\right)\approx-\frac{E-E_R}{\Gamma/2}=\frac{E_R-E}{\Gamma/2}$$

$$\rightarrow f_l\approx\frac{1}{\dfrac{(E_R-E)}{\Gamma/2}-i}=\frac{\Gamma/2}{E-E_R+i\Gamma/2}\quad \text{Breit-Wigner resonant amplitude}$$

Resonant partial wave ≈ Total scattering amplitude at the resonance energy
E_R: characteristic energy of the system
$1/\Gamma$: Phase variation at $E_R \rightarrow [1/\Gamma]$ = Time

Observe:
Potential scattering : Approximation of (more fundamental) covariant amplitude
Same physics, different language

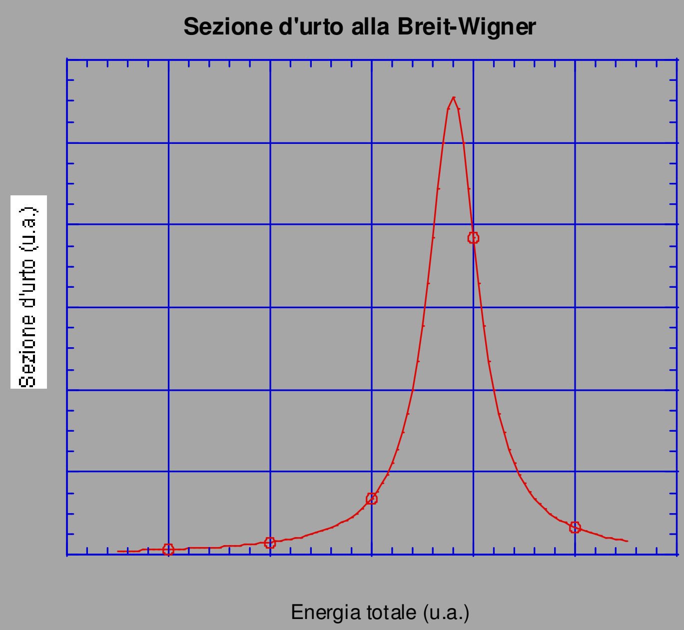
Resonances - III

Partial cross-section for l wave:

$$\rightarrow |f_l|^2 = \sin^2 \delta_l = \frac{\Gamma^2/4}{(E-E_R)^2 + \Gamma^2/4},$$

Total cross-section= Sum of partial wave cross-sections

Often dominated by a resonance in one partial wave



Resonance 'symptoms':

a) Fast increasing phase shift, going through $\pi/2$ at maximum rate
b) $|f_l|^2$ strongly peaked
c) Wave function large
d) $d\delta/dk$, and delay, strongly peaked

Resonances - IV

Generalize concept of stationary state:

$$\psi(\mathbf{r},t)=\varphi(\mathbf{r})e^{-iE_0t}\rightarrow\int_{-\infty}^{+\infty}e^{-iE_0t}e^{iEt}dt=\delta(E-E_0)$$

(Amplitude to find energy E when system is prepared in the state ψ)

to a kind of non-stationary, decaying state

$$e^{-iEt}=e^{-i(E_0-i\Gamma)t}=e^{-iE_0t}e^{-\Gamma t},\quad t>0$$

Complex E: Just meaning "System is unstable"

$$\int_0^{+\infty}e^{-i(E_0-i\Gamma)t}e^{iEt}dt=\int_0^{+\infty}e^{-i(E_0-E-i\Gamma)t}dt=-\frac{1}{i(E_0-E-i\Gamma)}e^{-i(E_0-E-i\Gamma)t}\Big|_0^{+\infty}=\frac{i}{(E-E_0+i\Gamma)}$$

(Breit-Wigner:

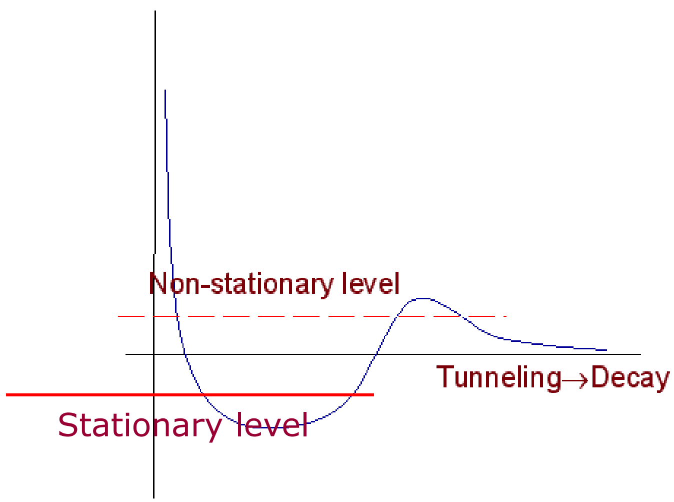
Amplitude to find energy E when system prepared in the state ψ)

$$|\psi|^2\propto\left|\frac{i}{E-E_0+i\Gamma}\right|^2=\left|\frac{E-E_0-i\Gamma}{(E-E_0)^2+\Gamma^2}\right|^2=\frac{(E-E_0-i\Gamma)(E-E_0+i\Gamma)}{\left[(E-E_0)^2+\Gamma^2\right]^2}=\frac{\left((E-E_0)^2+\Gamma^2\right)}{\left[(E-E_0)^2+\Gamma^2\right]^2}=\frac{1}{(E-E_0)^2+\Gamma^2}$$

Resonances - V

Non-stationary levels may result from a particular shape of the effective potential
Non stationary, scattering state
But: *Almost* stationary…

Long lifetime, sharp quantum numbers: Like a *stable* state (Bohr, '30s)



$$\Gamma = \begin{matrix} \text{1/time constant of decaying state} \approx \text{time uncertainty} \\ \text{Half width at half maximum} \approx \text{energy uncertainty} \end{matrix} \Bigg\} \to \Delta E \Delta t \sim \Gamma \frac{1}{\Gamma} = 1$$

Δ Resonance Formation - I

Take πp scattering at low energy: use phase shift analysis
Some complication arising from spin 1/2

$k \sim m, r \le R = \dfrac{1}{m} \to l = kr \le 1$ Limited range, low energy: just 2 waves S and P

$$J = 1/2 \oplus 0 \oplus l = 1/2 \oplus l = \begin{cases} 1/2 & S-wave \\ 1/2, 3/2 & P-wave \end{cases}$$

Expand first incident wave:

$$e^{ikz} \underbrace{\chi_{1/2}^{+1/2}}_{\text{spin eigenstate}} = \frac{1}{2ikr}\sum_{l=0}^{1}(2l+1)\left(e^{ikr} - (-1)^l e^{-ikr}\right)P_l(\cos\theta)\chi_{1/2}^{+1/2}$$

$$e^{ikz}\chi_{1/2}^{+1/2} = \frac{1}{2ikr}\sum_{l=0}^{1}\sqrt{4\pi(2l+1)}\left(e^{ikr} - (-1)^l e^{-ikr}\right)Y_l^0(\cos\theta)\chi_{1/2}^{+1/2}$$

$$Y_l^0\chi_{1/2}^{+1/2} = \sqrt{\frac{l+1}{2l+1}}y_{l+1/2}^{+1/2} - \sqrt{\frac{l}{2l+1}}y_{l-1/2}^{+1/2}$$

Spin spherical harmonics

$$y_{l+1/2}^{+1/2} = \sqrt{\frac{l+1}{2l+1}}Y_l^0\chi_{1/2}^{+1/2} + \sqrt{\frac{l}{2l+1}}Y_l^1\chi_{1/2}^{-1/2}, \quad y_{l-1/2}^{+1/2} = \sqrt{\frac{l+1}{2l+1}}Y_l^1\chi_{1/2}^{-1/2} - \sqrt{\frac{l}{2l+1}}Y_l^0\chi_{1/2}^{+1/2}$$

Δ Resonance Formation - II

$$\frac{1}{2ikr}\sum_{l=0}^{1}\sqrt{4\pi(2l+1)}\left(e^{ikr}-(-1)^l e^{-ikr}\right)Y_l^0(\cos\theta)\chi_{1/2}^{+1/2}$$

$$=\frac{1}{2ikr}\sum_{l=0}^{1}\sqrt{4\pi(2l+1)}\left(e^{ikr}-(-1)^l e^{-ikr}\right)\left(\sqrt{\frac{l+1}{2l+1}}y_{l+1/2}^{+1/2}-\sqrt{\frac{l}{2l+1}}y_{l-1/2}^{+1/2}\right)$$

$$=\frac{1}{2ikr}\sum_{l=0}^{1}\sqrt{4\pi}\left(e^{ikr}-(-1)^l e^{-ikr}\right)\left(\sqrt{l+1}y_{l+1/2}^{+1/2}-\sqrt{l}\,y_{l-1/2}^{+1/2}\right)$$

Scattering amplitude: Phase shifts only modify *outgoing* spherical wave

$$f(\theta)=\frac{1}{2ik}\sum_{l=0}^{\infty}(2l+1)(a_l-1)P_l(\cos\theta)$$

$$\rightarrow f(\theta)=\frac{\sqrt{4\pi}}{2ik}\sum_{l=0}^{\infty}\left(\sqrt{l+1}y_{l+1/2}^{+1/2}\left(a_l^{+}-1\right)-\sqrt{l}\,y_{l-1/2}^{+1/2}\left(a_l^{-}-1\right)\right)$$

$$a_l^{\pm}=e^{2i\delta_l^{\pm}}-1$$

Δ Resonance Formation - III

Re-arrange scattering amplitude:

$$f(\theta)=\frac{1}{2ik}\sum_{l=0}^{1}\left[(l+1)\left(a_l^+-1\right)+l\left(a_l^--1\right)\right]P_l^0(\cos\theta)\chi_{1/2}^{+1/2}+\left(a_l^+-a_l^-\right)P_l^{+1}(\cos\theta)e^{i\varphi}\chi_{1/2}^{-1/2}$$

$$=\underbrace{\frac{1}{2ik}\sum_{l=0}^{1}\left[(l+1)\left(a_l^+-1\right)+l\left(a_l^--1\right)\right]P_l^0(\cos\theta)}_{g(\theta)}\chi_{1/2}^{+1/2}+\underbrace{\frac{1}{2ik}\sum_{l=0}^{1}\left(a_l^+-a_l^-\right)P_l^{+1}(\cos\theta)e^{i\varphi}}_{h(\theta)}\chi_{1/2}^{-1/2}$$

Spin <u>non-flip</u> amplitude — Spin <u>flip</u> amplitude

Differential cross-section:

$$\frac{d\sigma}{d\Omega}=\frac{1}{k^2}\left|g(\theta)\right|^2+\left|h(\theta)\right|^2 \quad g,h \text{ spin eigenfunctions orthogonal}$$

$$P_0^0=1,\ P_1^0=\cos\theta,\ P_1^{+1}=-\sin\theta \quad \text{Associate Legendre functions}$$

$$\frac{d\sigma}{d\Omega}=\frac{1}{k^2}\left|\left(a_0^+-1\right)+\left[2\left(a_1^+-1\right)+\left(a_1^--1\right)\right]\cos\theta\right|^2+\left|\left(a_1^+-a_1^-\right)(-\sin\theta)\right|^2$$

$$\rightarrow\frac{d\sigma}{d\Omega}=\frac{1}{k^2}\left(A_0+A_1\cos\theta+A_2\cos^2\theta\right),\ \ A_0,A_1,A_2 \text{ Energy dependent coefficients}$$

Δ Resonance Formation - IV

Around $\sqrt{s} \sim 1230$ MeV find

$$\frac{d\sigma}{d\Omega} = \frac{1}{k^2}\left(1 + 3\cos^2\theta\right)$$

consistent with the decay of a *J=3/2* state

Indeed, taking for example $J_z = +1/2$:

$$\left|3/2, +1/2\right\rangle = \sqrt{\frac{1}{3}}\left|1/2, -1/2\right\rangle Y_1^{+1} + \sqrt{\frac{2}{3}}\left|1/2, +1/2\right\rangle Y_1^0$$

$$\frac{dN}{d\Omega} \propto \frac{1}{3}\left|Y_1^{+1}\right|^2 + \frac{2}{3}\left|Y_1^0\right|^2 = \frac{1}{3}\frac{1}{2}\sin^2\theta + \frac{2}{3}\cos^2\theta = \frac{1}{6} + \frac{3}{6}\cos^2\theta \propto 1 + 3\cos^2\theta$$

Width:

ΔE = Breit-Wigner full width at half maximum $\sim$ 100 MeV

$\Delta t \sim 1/\Delta E = 1/100\ MeV^{-1}$

$\rightarrow \Delta t = 10^{-2} \cdot \hbar c \cdot 1/c = 10^{-2}$ 197 MeV fm $\cdot$ $1/\left(3\times10^{23}\text{ fm s}\right) \sim 0.7\ 10^{-23}$ s

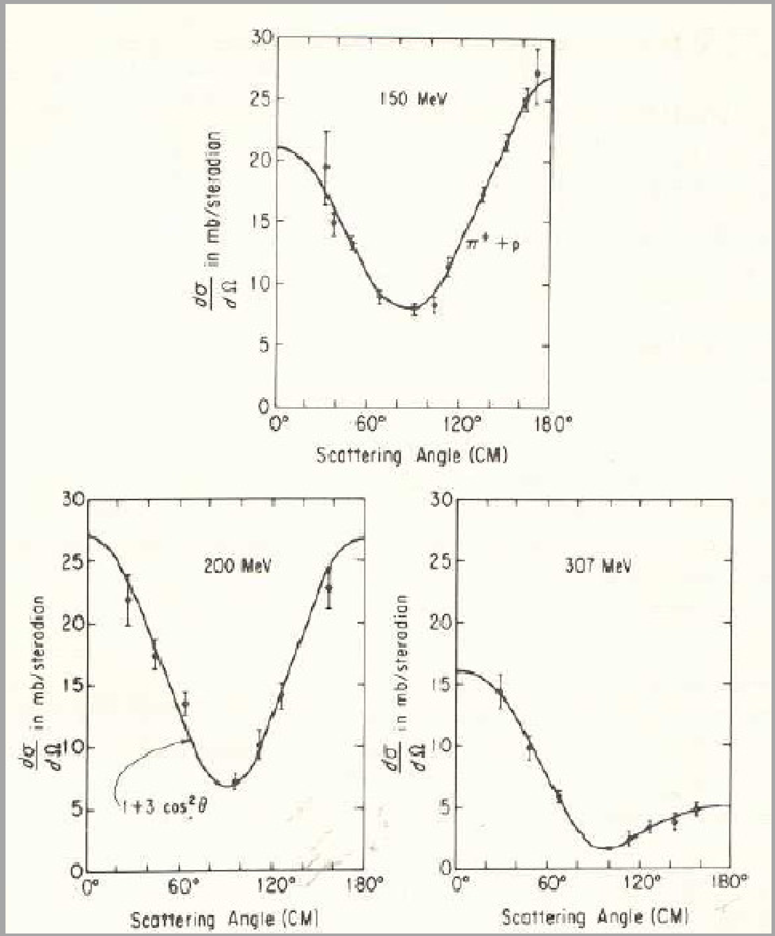
Parity $\quad \eta_\Delta = \eta_p \eta_\pi \eta_{orb} = (+1)(-1)(-1)^{l=1} = +1$

Δ Angular Distributions

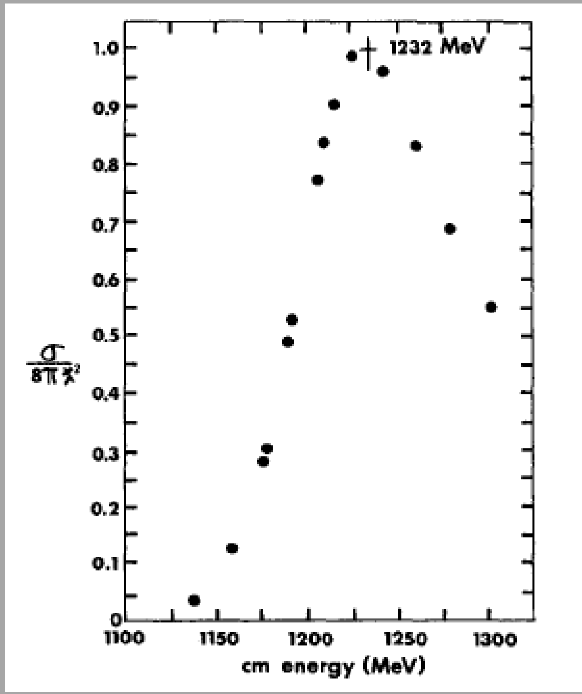
Experimental data nicely fit a simple picture where around $T_p = 200$ MeV the dominant amplitude is *J=3/2,* namely:

The large peak observed in the total cross-section can be traced back to a resonant amplitude in the L=1, J=3/2 partial wave

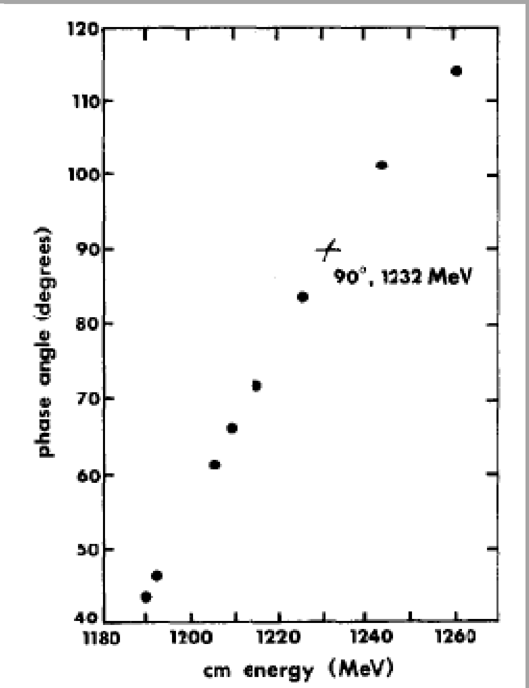
Several attempts to recover phase shifts from data in this energy range (Fermi, …): Messy game, lots of ambiguities



Δ^{++} : More Fingerprints



Cross-section



Phase

Propagators in the *t*-channel - I

The same propagator describes the *t*-channel amplitude, $t=q^2<0$:

$$\frac{1}{q^2\left(1-\overline{\Pi}_\gamma^{(2)}\left(q^2\right)\right)} \approx \frac{1}{q^2-M\left(M-i\Gamma\right)} \underset{\Gamma \ll M}{\approx} \frac{1}{q^2-M^2}$$ 'Pole' amplitude

In this case, there is *no* resonant behavior: $q^2-M^2<0$ strictly

Rather, the amplitude can be seen as an extension of the virtual photon idea, corresponding to the exchange of a *virtual particle*, with mass M and width Γ, or lifetime $1/\Gamma$. In the previous example, it would be a *virtual muonic atom.*

As for the virtual photon , the virtual particle exchanged is said to be *off mass-shell*: $q^2 \neq M^2$

Largest contribution from lightest (virtual) particles:

Exchange of virtual pions dominating at low q^2

Propagators in the *t*-channel - II

Take *NN* scattering at small q^2 as dominated by *one pion exchange*:
This *can* be maintained, to some extent (or so one believes).
Then

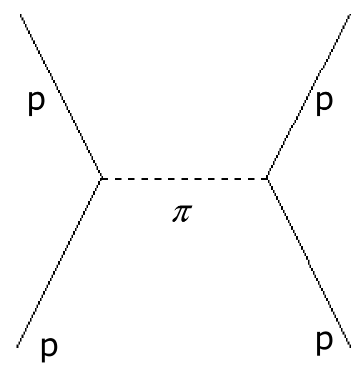
$$A \propto \frac{1}{q^2 - m_\pi^2}$$

In the static potential limit

$$E_C \approx E_A$$

$$q^2 = \left(E_C - E_A\right)^2 - \left(\mathbf{p}_C - \mathbf{p}_A\right)^2 \approx -\left(\mathbf{p}_C - \mathbf{p}_A\right)^2 = -\left|\mathbf{q}\right|^2$$

$$\rightarrow \frac{1}{q^2 - m_\pi^2} \approx \frac{1}{-\left|\mathbf{q}\right|^2 - m_\pi^2} = -\frac{1}{\left|\mathbf{q}\right|^2 + m_\pi^2}$$



Assuming Born approximation

$$V(r) \propto \int e^{i\mathbf{q}\cdot\mathbf{r}} \left(-\frac{1}{\left|\mathbf{q}\right|^2 + m_\pi^2} \right) d^3\mathbf{q} \propto -\frac{e^{-m_\pi r}}{r}$$ Yukawa potential

→ Potential scattering formalism useful

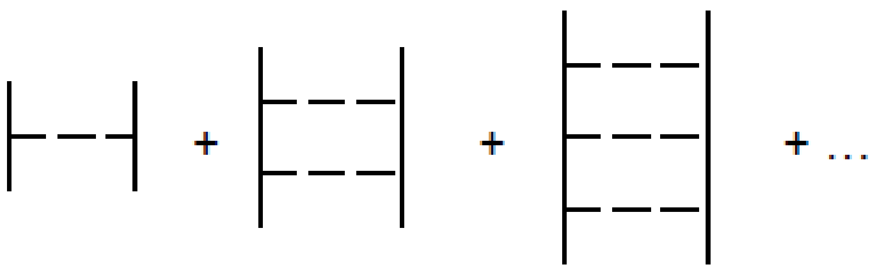
Propagators in the *t*-channel - III

Very appealing as a qualitative visualization of processes
Also superficially consistent with perturbative expansion:
Just include diagrams with 2,3,… virtual particles

But:

…Unfortunately not very useful as a tool for quantitative work in strong interactions physics: perturbative expansion cannot be maintained for large coupling constant ...

Most simply: Diagrams with more than one particle exchanged yielding amplitudes *larger* than diagrams with just one



$$|A_1| \quad < \quad |A_2| \quad < \quad |A_3| < \ldots$$

Production Resonances

With higher energy beams available, new processes become possible.
Use *virtual pions* to excite nucleon levels

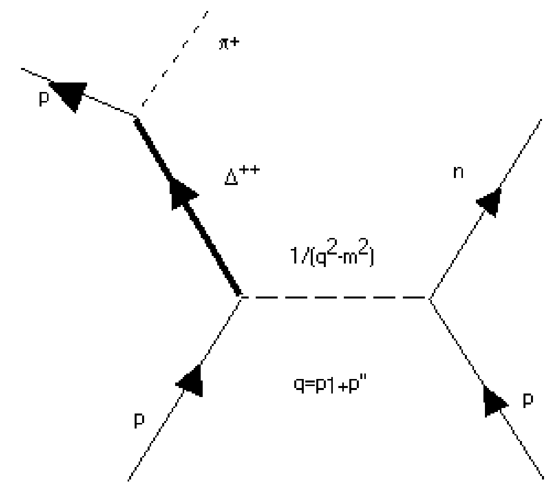
$$p + p \rightarrow n + \Delta^{++} \rightarrow n + p + \pi^{+}$$

Resonance is *produced* in the *t*-channel, rather than *formed* in the *s*-channel.

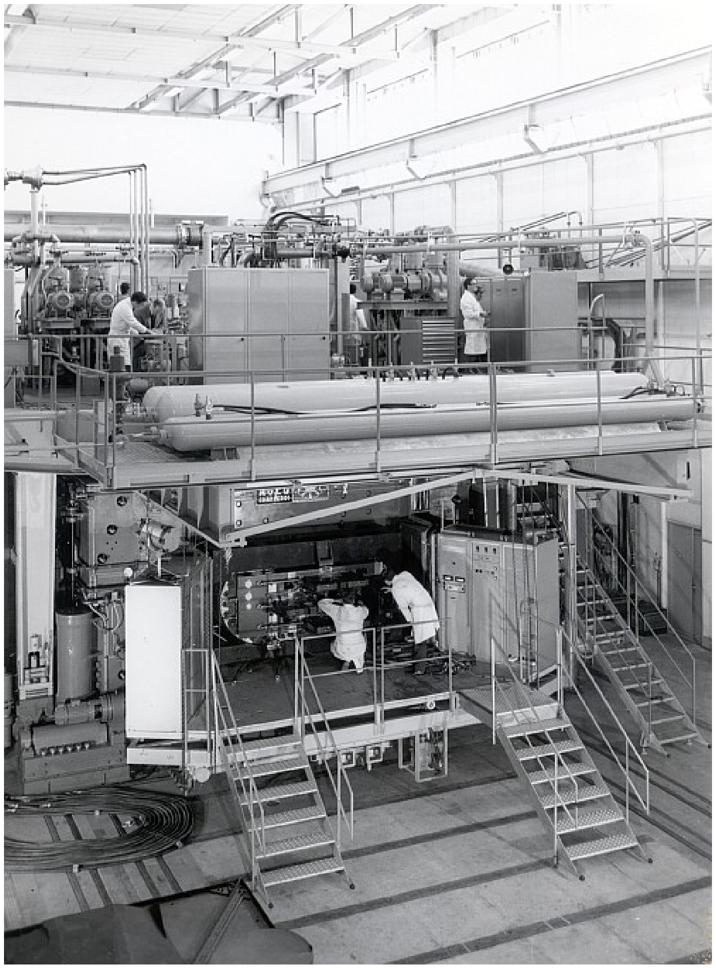
Strong interaction between exchanged *virtual* pion and real proton similar to interaction between *real* pion and proton

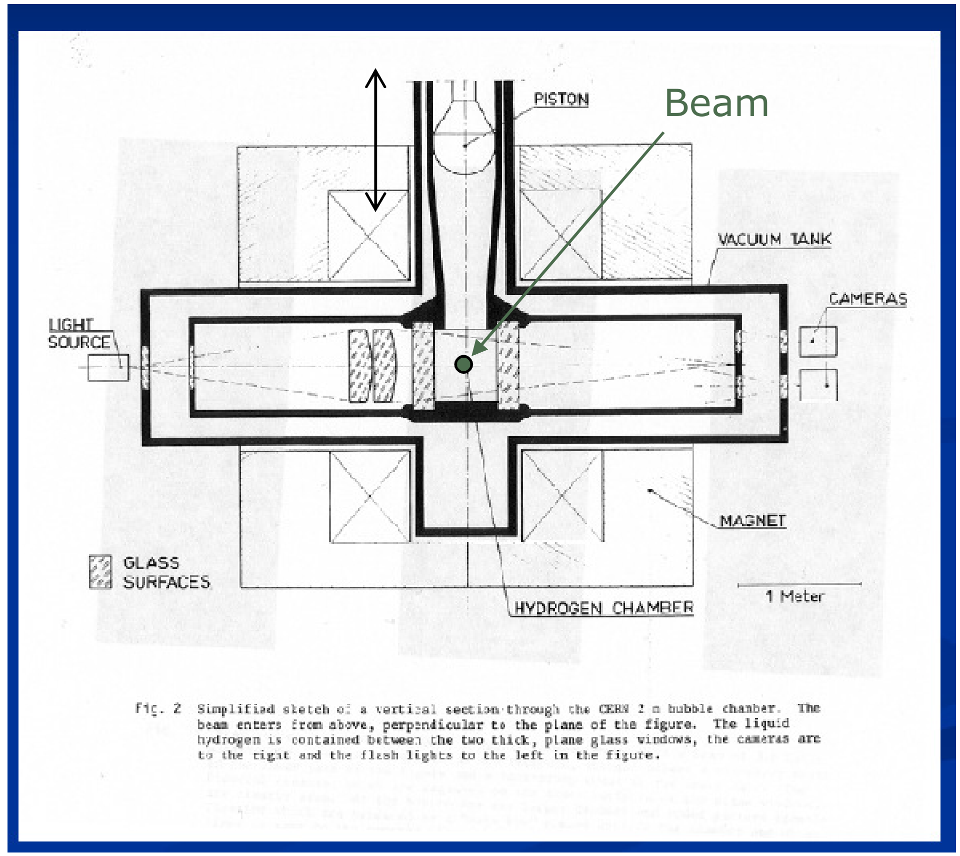
Not directly observed in the cross-section vs. energy plot.

But: Resonance mass and quantum numbers are *invariant* properties, like the corresponding quantities of a stable particle



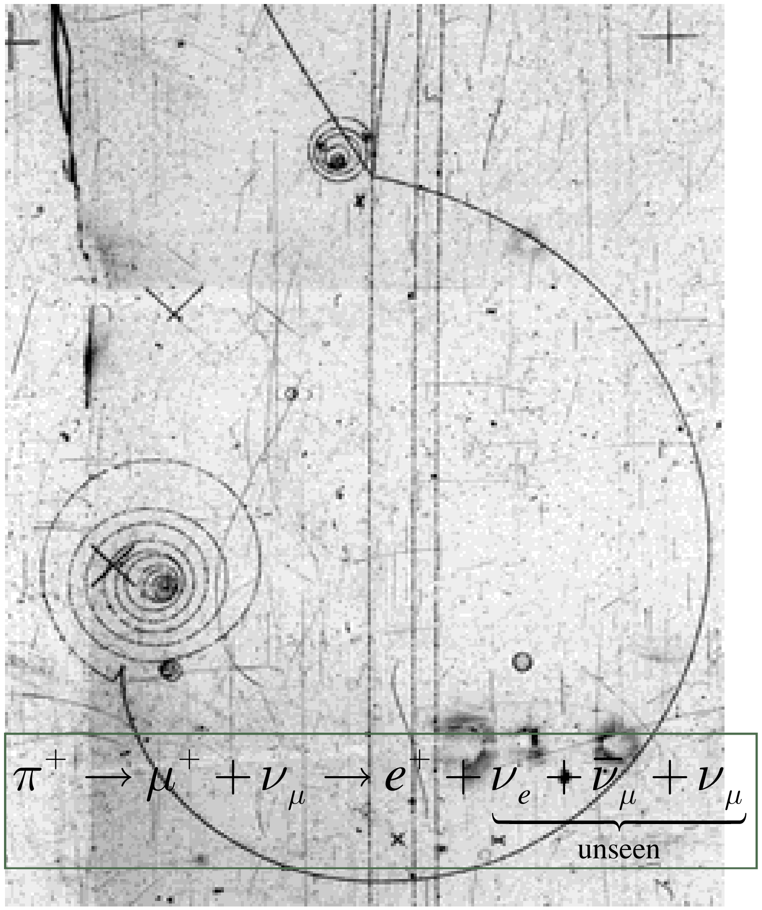
The Bubble Chamber



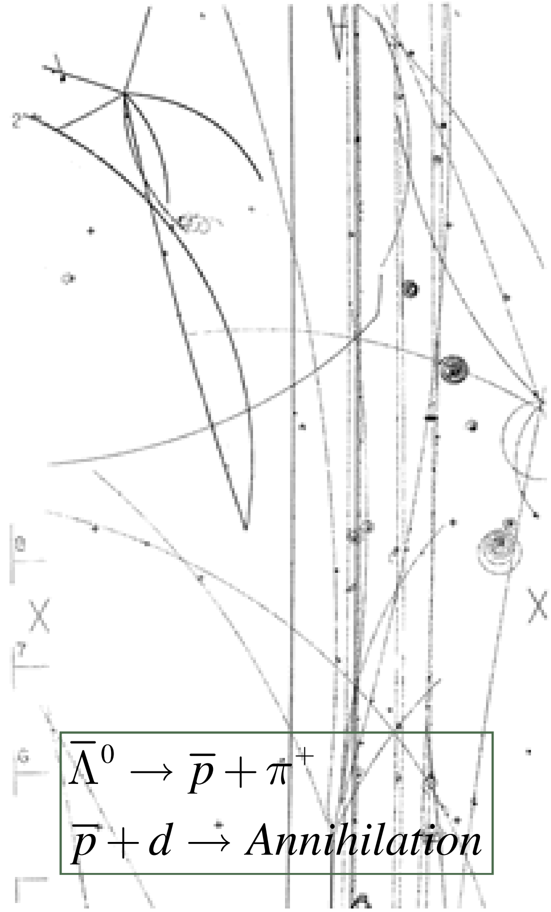


CERN 2m Bubble Chamber

Bubble Chamber Events - I



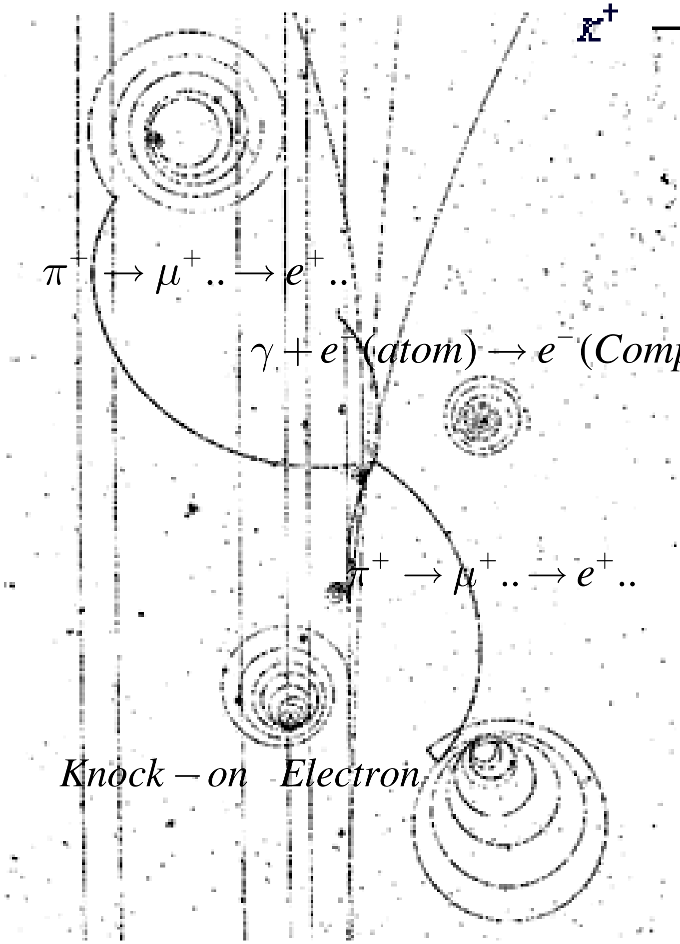
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \underbrace{\nu_e + \overline{\nu}_\mu + \nu_\mu}_{\text{unseen}}$$

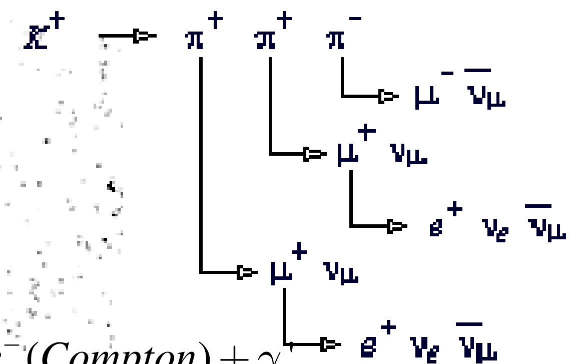


$$\overline{\Lambda}^0 \rightarrow \overline{p} + \pi^+$$

$$\overline{p} + d \rightarrow Annihilation$$

Bubble Chamber Events - II





<u>Knock-On electron</u>

$Beam + Atomic\ Electron$

$\to Beam + \ Free\ Electron$

Electromagnetic process

Usually modest energy

Bubble Chamber Events - III

$\pi\mu\varepsilon$ kinematics

π^+ only: π^- is usually captured to a π - *mesic* atom

π decays after stopping: 'long' lifetime..

μ Energy, momentum:

$$E_\mu = \frac{1}{2m_\pi}\left(m_\pi^2 + m_\mu^2 - 0\right) \sim 109.9\ MeV \rightarrow p_\mu = \sqrt{109.9^2 - 106^2} \sim 29.1\ MeV$$

$$\rightarrow \beta_\mu = \frac{p_\mu}{E_\mu} \sim \frac{29.1}{109.9} \sim 0.265, \gamma_\mu \sim 1.04 \text{ when created}$$

Would expect typical path length $\sim \beta_\mu \gamma_\mu c\tau_\mu \sim 182\ m$

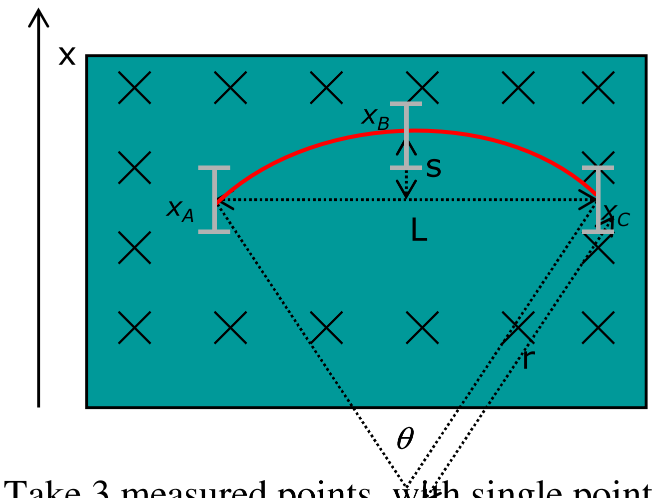
But: μ quickly slows down by $\frac{dE}{dx} \rightarrow$ Total path length $\sim$ few cm

Positron spiralling down: Energy loss by $\begin{cases} ionization \\ radiation \end{cases}$

Magnetic Analysis & Accuracy

Motion of a charged particle in a uniform magnetic field: Cylindrical helix coaxial to ***B***

$$r = \frac{p_\perp}{0.3B} \qquad r: \ m, \ p_\perp: \ GeV, \quad B: \ T$$



Get p from s

$$\sin\frac{\theta}{2} = \frac{L}{2r} \underset{L \ll 2r}{\rightarrow} \frac{\theta}{2} \approx \frac{L}{2r} \rightarrow \theta \approx \frac{0.3BL}{p_\perp}$$

$$s = r - r\cos\frac{\theta}{2} \approx r\left[1 - \left(1 - \frac{\theta^2}{4}\right)\right] = r\frac{\theta^2}{8} \approx \frac{0.3BL^2}{8p_\perp}$$

$$\rightarrow p_\perp \approx \frac{0.3BL^2}{8s}$$

Take 3 measured points, with single point accuracy σ

Then:

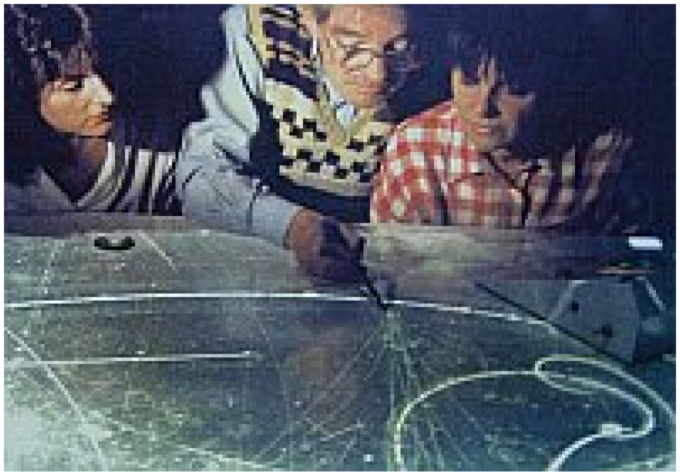
$$s = x_B - \frac{x_A + x_B}{2} \rightarrow \sigma_s^2 = \sigma^2 + \frac{1}{2}\sigma^2 = \frac{3}{2}\sigma^2$$

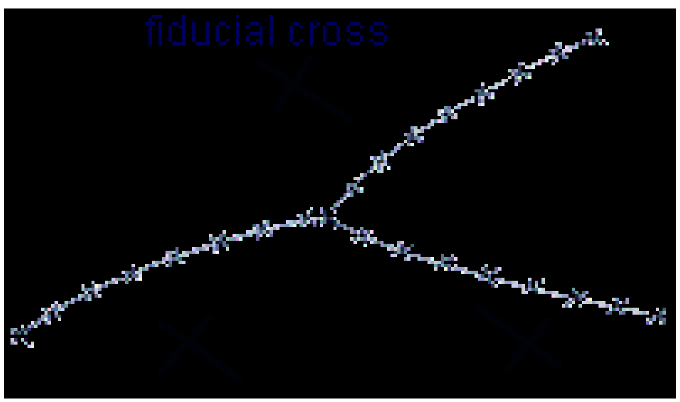
$$\frac{\sigma_{p_\perp}}{p_\perp} = \frac{\sigma_s}{s} = \sqrt{\frac{3}{2}}\frac{\sigma}{s} = \sqrt{\frac{3}{2}}\frac{\sigma 8 p_\perp}{0.3BL^2} = \sqrt{\frac{300 \cdot 64}{18}}\frac{\sigma p_\perp}{BL^2} \approx 32.7\frac{\sigma p_\perp}{BL^2}$$

$N \geq 10$, uniformly spaced points:

$$\frac{\sigma_{p_\perp}}{p_\perp} \approx 28.3\frac{\sigma p_\perp}{BL^2\sqrt{N+4}}$$

Bubble Chamber Reconstruction





Particle	p_x	p_y	p_z	E
K-	8213.4	-248.3	15.2	8232
p	0	0	0	938.3
Sum	8213.4	-248.3	15.2	9170.3
K-	1481.8	27.8	224	1578.1
p-	149.7	-11.3	38.8	208.6
p+	37.9	-122.2	-22.7	190.7
p	1508.6	128.5	-70.5	1782.6
K0	3545.6	-162.9	-245	3592.4
Sum	6723.6	-140.1	-75.4	7352.4
Difference	-1489.8	108.2	-90.6	-1817.9

mass	1032.153

This mass doesn't correspond to a known particle - so there must be at least two neutral particles from the collision leaving the bubble chamber undetected.

Δ-Resonance: Production

Observe Δ^{++} resonance production as a peak in the invariant (p,π^+) mass distribution

Take reaction

$$\pi^+ p \to \pi^+ p \pi^+ \pi^-$$

$$m_{p\pi_1}{}^2 = \left(p_p + p_{\pi_1}\right)^2 = \left(E_p + E_{\pi_1}\right)^2 - \left(\mathbf{p}_p + \mathbf{p}_{\pi_1}\right)^2$$

$$m_{p\pi_2}{}^2 = \left(p_p + p_{\pi_2}\right)^2 = \left(E_p + E_{\pi_1}\right)^2 - \left(\mathbf{p}_p + \mathbf{p}_{\pi_2}\right)^2$$

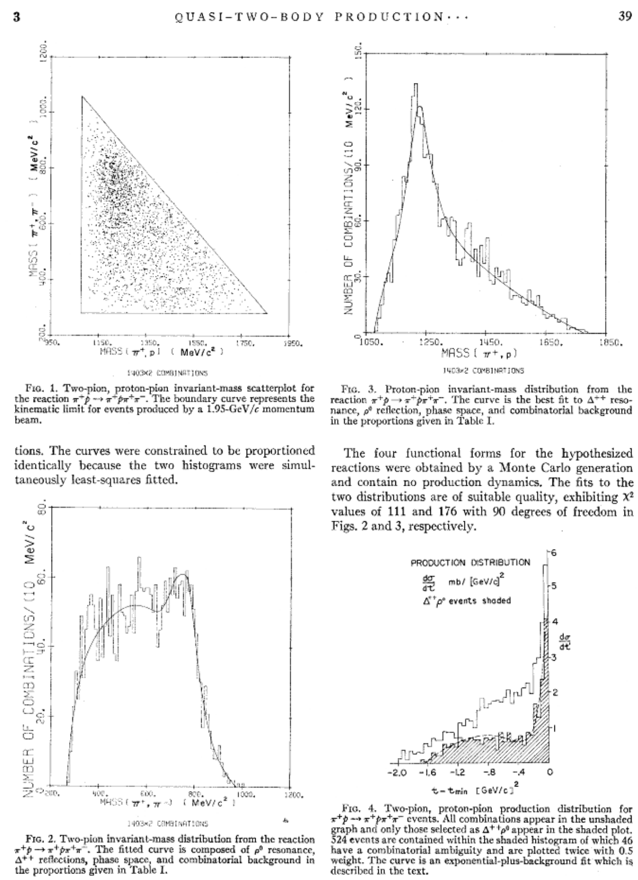

3 QUASI-TWO-BODY PRODUCTION··· 39

FIG. 1. Two-pion, proton-pion invariant-mass scatterplot for the reaction $\pi^+ p \to \pi^+ p \pi^+ \pi^-$. The boundary curve represents the kinematic limit for events produced by a 1.95-GeV/c momentum beam.

FIG. 3. Proton-pion invariant-mass distribution from the reaction $\pi^+ p \to \pi^+ p \pi^+ \pi^-$. The curve is the best fit to Δ^{++} resonance, ρ^0 reflection, phase space, and combinatorial background in the proportions given in Table I.

tions. The curves were constrained to be proportioned identically because the two histograms were simultaneously least-squares fitted.

The four functional forms for the hypothesized reactions were obtained by a Monte Carlo generation and contain no production dynamics. The fits to the two distributions are of suitable quality, exhibiting χ^2 values of 111 and 176 with 90 degrees of freedom in Figs. 2 and 3, respectively.

FIG. 2. Two-pion invariant-mass distribution from the reaction $\pi^+ p \to \pi^+ p \pi^+ \pi^-$. The fitted curve is composed of ρ^0 resonance, Δ^{++} reflections, phase space, and combinatorial background in the proportions given in Table I.

FIG. 4. Two-pion, proton-pion production distribution for $\pi^+ p \to \pi^+ p \pi^+ \pi^-$ events. All combinations appear in the unshaded graph and only those selected as $\Delta^{++}\rho^0$ appear in the shaded plot. 524 events are contained within the shaded histogram of which 46 have a combinatorial ambiguity and are plotted twice with 0.5 weight. The curve is an exponential-plus-background fit which is described in the text.

Meson Resonances - I

Expect resonant behavior also for mesonic systems, e.g. $\pi\pi$:
Virtual and real pion coupled at the strong vertex

Observation of meson resonances possible in production experiments

Remark:

Taking baryon resonances only, possible isospin:

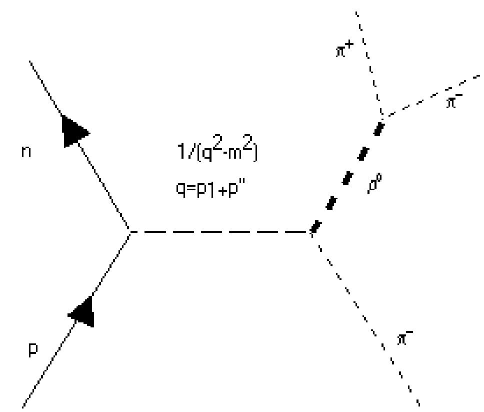
Minimum coupling is between nucleon and pion

$\rightarrow$ Expect $1 \oplus 1/2 = 1/2, 3/2$ as observed

Take meson resonances:

Minimum coupling is between pion and pion

$\rightarrow$ Expect $1 \oplus 1 = 0, 1, 2$ I=2 mesons not observed



Meson Resonances - II

Take reaction

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

Observe strong enhancements for

$$m_{\pi\pi} \sim 760,\ 1260,\ 1550 \quad MeV$$
$$m_{\pi n} \sim 1230 - 1550 \quad MeV$$

Interpretation:

Meson Baryon Resonances

$$\left.\begin{matrix} \rho(760) \\ f_0(1250) \\ g(1550) \end{matrix}\right\} \rightarrow \pi^\pm \pi^\mp, \quad \Delta^{+,-}(1232) \rightarrow n\pi^\pm$$

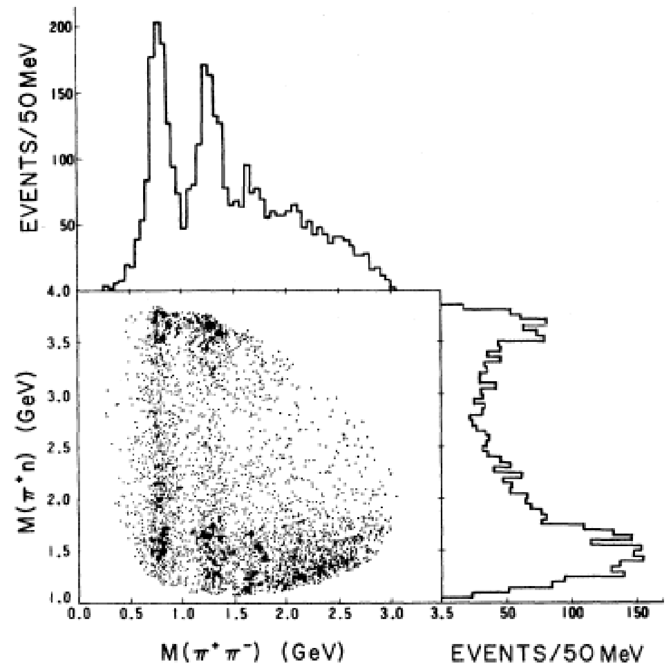


FIG. 2. Scatter plot of $M(\pi^+\pi^-)$ versus $M(\pi^+ n)$ with the projections on both axes.

Spin-parity of the ρ Meson - I

Use angular distributions to investigate ρ spin, parity

$$S_\pi = 0 \rightarrow J_\rho = L_{\pi\pi} \equiv L$$

$$\rightarrow \psi_{final} \propto Y_l^m(\theta,\varphi)$$

$$\eta_P^{(\rho)} = \eta_P^{(\pi)}\eta_P^{(\pi)}(-1)^l = (-1)^l$$

Suppose the produced ρ mesons uniformly populate the *2l+1* J_3 substates: Then, by a property of spherical harmonics

$$\frac{dP}{d\Omega} = \frac{1}{2J+1}\sum_{m=-l}^{+l} Y_l^m(\theta,\varphi)Y_l^{*m}(\theta,\varphi); \quad \sum_{m=-l}^{+l} Y_l^m Y_l^{*m} = \frac{2l+1}{4\pi}$$

$$\rightarrow \frac{dP}{d\Omega} = \frac{1}{2J+1}\frac{2J+1}{4\pi} = \frac{1}{4\pi} \quad \text{Uniform distribution}$$

So a non-uniform angular distribution indicates some *polarization* of the decaying state, useful to perform spin-parity analysis

Spin-parity of the ρ Meson - II

Observe CM angular distribution for different $\pi\pi$ mass 'slices'

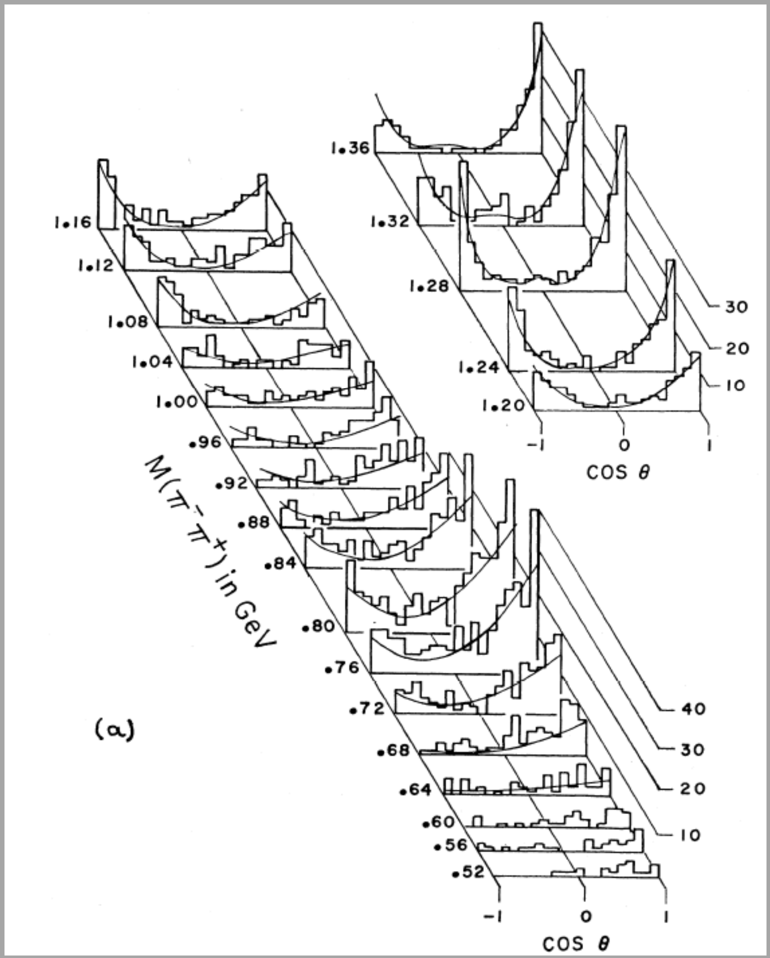
In the ρ resonance mass region (about 700-800 MeV)

$$\frac{dP}{d\Omega} \propto \cos^2\theta \propto \left|Y_1^0(\cos\theta)\right|^2 \to l = 1$$

$\to$ The ρ is a *vector* particle

Interestingly, in the f_0 mass region (about 1250-1350 MeV) observe some indication of spin 2

$$\frac{dP}{d\Omega} \propto \left(3\cos^2\theta - 1\right)^2 \propto \left|Y_2^0\right|^2 \to l = 2$$



Isospin - I

Charge independence leads to a new classification scheme:
All hadrons cast into *isospin multiplets*
Strong interaction identical for all members of each multiplet

$$\left.\begin{array}{l}\text{proton } p \\ \text{neutron } n\end{array}\right\} 2 \text{ states of the } \textit{nucleon} \quad N = \begin{pmatrix}\alpha \\ \beta\end{pmatrix} \quad \text{2 states system - isospinor}$$

$$\text{Base } \begin{pmatrix}1 \\ 0\end{pmatrix} \equiv p, \quad \begin{pmatrix}0 \\ 1\end{pmatrix} \equiv n \qquad \text{Base states: } \textit{doublet}$$

$$\left.\begin{array}{l}\pi^+ \\ \pi^0 \\ \pi^-\end{array}\right\} 3 \text{ states of the } \textit{pion} \quad \pi = \begin{pmatrix}\alpha \\ \beta \\ \gamma\end{pmatrix} \quad \text{3 state system - isovector}$$

$$\text{Base } \begin{pmatrix}1 \\ 0 \\ 0\end{pmatrix} \equiv \pi^+, \begin{pmatrix}0 \\ 1 \\ 0\end{pmatrix} \equiv \pi^0, \begin{pmatrix}0 \\ 0 \\ 1\end{pmatrix} \equiv \pi^- \qquad \text{Base states: } \textit{triplet}$$

Isospin - II

Isospins add up as angular momenta (Astonished? More on this later…)
For πN system obtain:

$$\left.\begin{array}{l}\pi : I = 1 \\ N : I = 1/2\end{array}\right\} \rightarrow \pi N : I = 1 \oplus 1/2 = \begin{cases} 1/2 & \text{doublet} \\ 3/2 & \text{quadruplet} \end{cases}$$

By using Clebsch-Gordan coefficients, expand physical (particle) states into total isospin eigenstates

Single particle: Base states

$$I_N = 1/2 \;\; ; \;\; |\mathrm{p}\rangle = |1/2, +1/2\rangle \;\; , \;\; |\mathrm{n}\rangle = |1/2, -1/2\rangle$$

$$I_\pi = 1 \;\; ; \;\; |\pi^+\rangle = |1, +1\rangle \;\; , \;\; |\pi^0\rangle = |1, 0\rangle \;\; , \;\; |\pi^-\rangle = |1, -1\rangle$$

Isospin - III

Expand physical, 2 particle states into total isospin eigenstates:

$$\left|\pi^- p\right\rangle = \left|1,-1,1/2,+1/2\right\rangle = \sqrt{\frac{1}{3}}\left|3/2,-1/2\right\rangle - \sqrt{\frac{2}{3}}\left|1/2,-1/2\right\rangle$$

$$\left|\pi^+ n\right\rangle = \left|1,+1,1/2,-1/2\right\rangle = \sqrt{\frac{1}{3}}\left|3/2,+1/2\right\rangle + \sqrt{\frac{2}{3}}\left|1/2,+1/2\right\rangle$$

$$\left|\pi^+ p\right\rangle = \left|1,+1,1/2,+1/2\right\rangle = \left|3/2,+3/2\right\rangle$$

$$\left|\pi^- n\right\rangle = \left|1,-1,1/2,-1/2\right\rangle = \left|3/2,-3/2\right\rangle$$

$$\left|\pi^0 p\right\rangle = \left|1,0,1/2,+1/2\right\rangle = \sqrt{\frac{2}{3}}\left|3/2,+1/2\right\rangle - \sqrt{\frac{1}{3}}\left|1/2,+1/2\right\rangle$$

$$\left|\pi^0 n\right\rangle = \left|1,0,1/2,-1/2\right\rangle = \sqrt{\frac{2}{3}}\left|3/2,-1/2\right\rangle + \sqrt{\frac{1}{3}}\left|1/2,-1/2\right\rangle$$

Isospin - IV

Guess isospin is a new *symmetry* for hadrons: connect to some *invariance* property (like angular momentum).
Non-trivial conservation rule follows:

Total isospin conserved by all strong processes

Interesting predictions for πN scattering and reactions:

$$\begin{cases} (A)\,\pi^+ p \to \pi^+ p \\ (B)\,\pi^- n \to \pi^- n \end{cases} \to A_A = A_B = A_{3/2} \quad \text{pure I = 3/2}$$

$$\begin{cases} (A)\,\pi^+ n \to \pi^+ n \\ (B)\,\pi^- n \to \pi^- n \end{cases} \to A_A = \frac{1}{3}A_{3/2} + \frac{2}{3}A_{1/2}, A_B = A_{3/2}$$

$$\begin{cases} (A)\,\pi^+ p \to \pi^+ p \\ (B)\,\pi^- p \to \pi^- p \end{cases} \to A_A = A_{3/2}, A_B = \frac{1}{3}A_{3/2} - \frac{2}{3}A_{1/2}$$

$$\begin{cases} (A)\,\pi^+ p \to \pi^+ p \\ (B)\,\pi^- p \to \pi^0 n \end{cases} \to A_A = A_{3/2}, A_B = \sqrt{\frac{2}{9}}A_{3/2} - \sqrt{\frac{2}{9}}A_{1/2}$$

Isospin - V

If $A_{3/2}$>>$A_{1/2}$

$$\begin{cases}(A)\,\pi^+ p \to \pi^+ p \\ (B)\,\pi^- n \to \pi^- n\end{cases} \to \sigma_A = \sigma_B$$

$$\begin{cases}(A)\,\pi^+ n \to \pi^+ n \\ (B)\,\pi^- n \to \pi^- n\end{cases} \to \sigma_A \simeq \frac{1}{9}\sigma_B$$

$$\begin{cases}(A)\,\pi^+ p \to \pi^+ p \\ (B)\,\pi^- p \to \pi^- p\end{cases} \to \sigma_A \simeq 9\sigma_B$$

$$\begin{cases}(A)\,\pi^+ p \to \pi^+ p \\ (B)\,\pi^- p \to \pi^0 n\end{cases} \to \sigma_A \simeq \frac{9}{2}\sigma_B$$

Still lacking: *What exactly is isospin?*

What is Spin? - I

For any physical system with *m>0*, we are allowed to choose CM as a reference frame.

When the system is rotationally invariant, states are observed to group into multiplets of size *n*, *n=1,2,3,… (size n = number of states)*

States of a multiplet: *Same energy*

States belonging to different multiplets must be distinguished by some internal quantum number: Provisionally call the corresponding observable the particle *spin*

States of any given multiplet must be identified by some internal quantum number: Provisionally call the corresponding observable the *3rd component of the particle spin*

What is Spin? - II

Question: *What is the observable we have called spin?*

Answer: *Get some insight from conservation laws*.

Discover spin is just another kind of (non-orbital) angular momentum

$\mathbf{J} = \mathbf{L} + \mathbf{S}$ Total angular momentum

For any system: Extend to $\boldsymbol{S}$ known properties of $\boldsymbol{L}$

(S_x, S_y, S_z) analogue to (L_x, L_y, L_z):

Hermitian operators, infinitesimal generators of rotations around *x, y, z*

Commutators:

By assuming rotational invariance, in the CM H and $\boldsymbol{S}^2$ commute $\rightarrow$ $\boldsymbol{S}^2$, S_3 are conserved

$\left[S_x, S_y \right] = iS_z$ + Cyclical permutations

What is Spin? - III

Besides other quantum numbers, in the CM reference frame all possible stationary states are then labeled by $\mathbf{S}^2$, S_3 according to angular momentum algebra:

$$S^2 \text{ Eigenvalues: } \quad s\left(s+1\right),\ s\ =\ 0,1/2,1,3/2,2,...$$

Sequence of multiplets

$$S_3 \text{ Eigenvalues: } \underbrace{-s...+s}_{2j+1},\quad 2s+1\ \equiv\ \text{Multiplet size } 1,2,3,4,5,..$$

Each multiplet understood to realize an *irreducible representation* of some (unknown) symmetry group in the Hilbert space

NB Multiplets with even multiplicity *are* observed $\rightarrow 2j+1 = 2,4,\ldots$

Implies *j* can be *integer* or *half-integer*

What is Spin? - IV

Representation:

A set of matrices acting on some kind of 'vectors', labeled by the integer ***2s+1***

→Must have 3 independent matrices (= S_x, S_y, S_z*) for each rep.*

→Must have 2j+1 independent 'vectors' (= base states) for each rep

Size of matrices: *(2s+1) x (2s+1)*

Each matrix correspond to a *specific rotation*

→Must depend on 3 parameters (= rotation angles)

What is Spin? - V

Integer *s*: Like *l*

L eigenvalues are integer only *0,1,2,…*$\rightarrow$ *2l+1 = 1,3,5,..* odd integer

l identifies an *irreducible representation* of the rotation group *SO(3)*

(L_x,L_y,L_z): 3 matrices of size *1x1*, *3x3, 5x5*, … operating on different objects of size *1, 3, 5, …* *Spherical Tensors* (e.g. Spherical Harmonics)

Half-integer *s*: Minimum size is for *s=1/2* $\rightarrow$ *2 x 2*

2-component 'vectors' acted upon by *2 x 2* matrices called *spinors*
Not really like ordinary vectors

From the algebraic properties of ***S***:
Spin symmetry group must be a close relative of *SO(3)*
Just including extra values for *s* as compared to *l*

Matrix Fun - I

Take $j=1/2$:
Must represent rotations of 2-component spinors by *2x2* matrices

1) Naive attempt: Try with orthogonal matrices

$$M \equiv \begin{pmatrix} a & b \\ c & d \end{pmatrix} \text{ orthogonal}$$

$$\to MM^T = 1$$

$$\to \begin{pmatrix} a & b \\ c & d \end{pmatrix}\begin{pmatrix} a & c \\ b & d \end{pmatrix} = \begin{pmatrix} a^2+b^2 & ac+bd \\ ac+bd & c^2+d^2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\to \begin{cases} a^2+b^2=1 \\ c^2+d^2=1 \quad \& \; a,b,c,d \text{ real} \\ ac+bd=0 \end{cases}$$

$\to$ 1 free parameter

$\to$ KO to represent a 3D rotation

Matrix Fun - II

2) Better approach: Unitary matrices

$$U \equiv \begin{pmatrix} a & b \\ c & d \end{pmatrix} \text{ unitary} \rightarrow UU^{\dagger} = 1 \rightarrow \begin{pmatrix} a & b \\ c & d \end{pmatrix}\begin{pmatrix} \overline{a} & \overline{c} \\ \overline{b} & \overline{d} \end{pmatrix} = \begin{pmatrix} a\overline{a} + b\overline{b} & a\overline{c} + b\overline{d} \\ c\overline{a} + d\overline{b} & c\overline{c} + d\overline{d} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\rightarrow \begin{cases} a\overline{a} + b\overline{b} = 1 \\ c\overline{c} + d\overline{d} = 1 \;\; \& \; a,b,c,d \text{ complex} \rightarrow 4 \text{ free parameters} \\ a\overline{c} + b\overline{d} = 0 \\ c\overline{a} + d\overline{b} = 0 \end{cases}$$

Require extra condition:

$\det M = 1 \rightarrow ad - bc = 1 \rightarrow 3$ free parameters

$\rightarrow$ OK to represent a 3D rotation

Possible because absolute phase of states is irrelevant

Matrix Fun - III

Set of all *2x2* matrices satisfying the 4 conditions above:
A group, called the *Special Unitary group of dimension 2*, or *SU(2)*.

SU(2) vs SO(3):
3 parameters → 3 generators
Commutators identical→They share the same *algebra*

The moral:

O(3) and *SU(2)* are *more or less* the same group

→ All the irr.reps of *SO(3)* are also good for *SU(2)*

$SU(2)$ - I

Instead of starting from rotations, just start from $SU(2)$ defined as the set of all the $2x2$, unitary matrices (with $det=1$)

Not bound to understand this transformation of states as induced by a rotation of axis in the physical, 3D space.

Free to interpret any SU(2) matrix as representing a unitary, unimodular transformation in the Hilbert space of any two-state, degenerate system.

Do not need to specify what is the physical system whose two independent states we take as base vectors in the Hilbert space.

$SU(2)$ - II

Some matrix fun:

4 complex parameters $\rightarrow$ 8 real parameters

4 unitarity conditions: $\left.\begin{array}{r} UU^{\dagger}=1 \\ \left(U^{\dagger}\right)_{ij}=U_{ji}^{*} \end{array}\right\} \rightarrow \sum_{j=1}^{2} a_{ij} a_{jk}^{*}=\delta_{ik}, \quad i,k=1,2$

1 unimodularity condition: $\det U = 1$

$\rightarrow 8-5=3$ free parameters

One diagonal generator, s_3

$\rightarrow$*Rank 1 group*

$\rightarrow$ *One* invariant function of generators

Quadratic:

$\boldsymbol{\sigma}^2=\sigma_1^2+\sigma_2^2+\sigma_3^2$

SU(2) - III

Some insight into *SU(2)* generators:

U unitary $\rightarrow U = e^{iH}, H$ Hermitian

$\det U = 1 \rightarrow \det e^{iH} = 1 \rightarrow e^{itr(H)} = 1 \rightarrow tr(H) = 0$

3 free parameters $\rightarrow$ 3 generators

3 Hermitian, traceless 2×2 matrices

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Any *SU(2)* matrix can be written as a linear combination of the 3 generators: *Pauli matrices*

What is Isospin? - I

When looking at strongly interacting particles, observe particle states similarly grouping themselves into multiplets of size *1,2,3,4*

States of a multiplet $\cong$ *Same mass*

$\rightarrow$States belonging to different multiplets must be distinguished by some internal quantum number:
By analogy, call the corresponding observable the particle *isospin*

$\rightarrow$States of any given multiplet must be identified by some *internal* quantum number:
Call the corresponding observable the *3rd component of the particle isospin*

What is Isospin? - II

Notice: Isospin symmetry is not exact (broken), still is quite good
Indeed, looking at symmetry breaking mass splittings:

$$\frac{m_n - m_p}{m_n} \simeq \frac{939.57 - 938.27}{939.57} \simeq 0.0014 \text{ Nucleon doublet}$$

$$\frac{m_{\pi^\pm} - m_{\pi^0}}{m_{\pi^\pm}} \simeq \frac{139.6 - 135.0}{139.6} \simeq 0.011 \text{ Pion triplet}$$

For a long time:
Breaking entirely blamed on electromagnetic effects, which is only partially true (e.g. neutral and charged members indeed have quite different e.m. interactions contributing to their mass).

Today:
Isospin taken as an ‘accidental’ symmetry, not due to some fundamental property of hadron constituents or strong interaction

What is Isospin? - III

Question: What is the observable we have called *isospin*?

Answer: *There is no classical analogy!*

Simply, as we observe the neutron and proton to be almost degenerate in mass, we can state they are just two states of the same physical system, the *nucleon.*

In this picture, nuclear constituents and their relatives (hadrons) have internal degrees of freedom with no classical analogue, quite relevant *upon neglecting electromagnetic and weak interactions*: related observables are indeed conserved

We guess the two nucleon states are the ‘vectors’ spanning the fundamental representation of a symmetry group, which we identify with *SU(2).*

What is Isospin? - IV

Guess: *SU(2)* is a symmetry of all the strongly interacting particles.

Therefore:

All strongly interacting particles should fill some SU(2) representation

This is actually true, after neglecting small symmetry breaking effects within each multiplet (see later)

As for any other symmetry, expect the invariance property to yield a conservation law

What is Isospin? - V

What is conserved in this case?
Since there is no classical analogy, stick to our algebraic skills to get insight

SU(2) algebra is just the same as *O(3),* so we can expect the same conserved observables for a closed system of strongly interacting particles:

$$\boldsymbol{J}^2, J_3 \leftrightarrow \boldsymbol{I}^2, I_3$$

This is the origin of the common wisdom *'Isospin is like Angular Momentum'*

SU(2) Multiplet Graphics

Within any given *SU(2)* multiplet, states can be represented as points on a straight line

Reason is the group structure of *SU(2)*:

3 parameters $\rightarrow$ *3 generators*

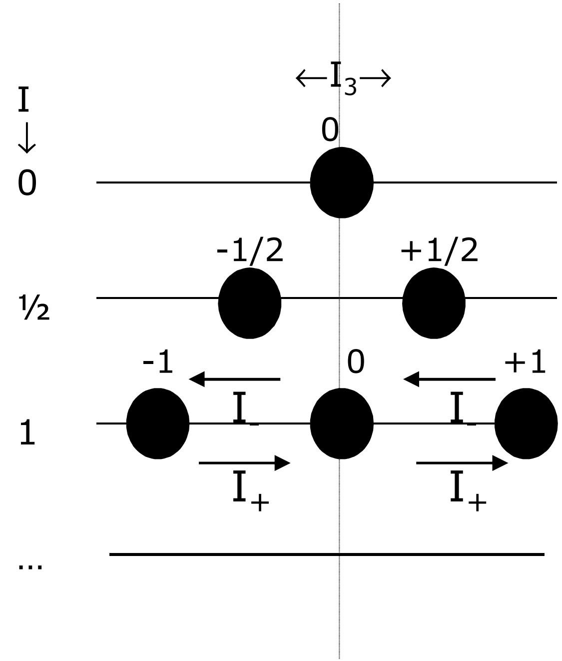
Just 1 invariant function of generators:
$\boldsymbol{I}^2 \rightarrow$ *Multiplets identified just by I*

Generators do not commute with each other
$\rightarrow$ *States in any multiplet identified just by* I_3

Define 2 *ladder operators*:

$I_{\pm} = I_1 \pm iI_2$

Observe:
I_3 eigenvalues *symmetric* wrt *0*



Action: Shift states right or left on the multiplet line, i.e. increment/ decrement I_3 by *1*

Conjugate Representation - I

More fun with matrices…

D : Any representation

$\psi^{'} = D(\alpha)\psi$

$\rightarrow D(\alpha) = e^{i\alpha F}$, F hermitian $\leftarrow$ True because D is unitary

Take complex conjugate of equations

$\psi^{'*} = D^{*}\psi^{*}$

Get another representation

$D^{*} = e^{-i\alpha(F)^{*}} = e^{i\alpha\left[-(F)^{*}\right]} \equiv e^{i\alpha\tilde{F}}$

Relation bewteen new and old generators

$\rightarrow \tilde{F} = -\left(F^{*}\right)$

Conjugate Representation - II

Take D of $SU(2)$ fundamental representation:

F Hermitian $\rightarrow \tilde{F}$ Hermitian

$\rightarrow$ Real eigenvalues for both $F, \tilde{F}$, and $f_i = -f_i^*$

$\rightarrow$ Since f_i are symmetric wrt 0, so are f_i^*

$\rightarrow \{f_i\} \equiv \{f_i^*\}$ $\quad \tilde{F}$ eigenvalues are just a re-labeling of F's

Direct and conjugate representations are said to be *equivalent*

True for SU(2), generally false

Product of Representations - I

Take a system made of 2 nucleons: *What is the total isospin?*
SU(2) is equivalent to *O(3)* → *Can use Clebsch-Gordan coefficients*

But: Can also re-formulate the problem in a different way
Each nucleon spans the fundamental representation of *SU(2)*, ***2***

Then a 2 nucleon system span the *direct product rep.* $\mathbf{2} \otimes \mathbf{2}$

Question:

What are the irreducible representations of SU(2) contained in any state of 2 nucleons?

Need to decompose $\mathbf{2} \otimes \mathbf{2}$ into a *direct sum* of irr.rep.

Product of Representations - II

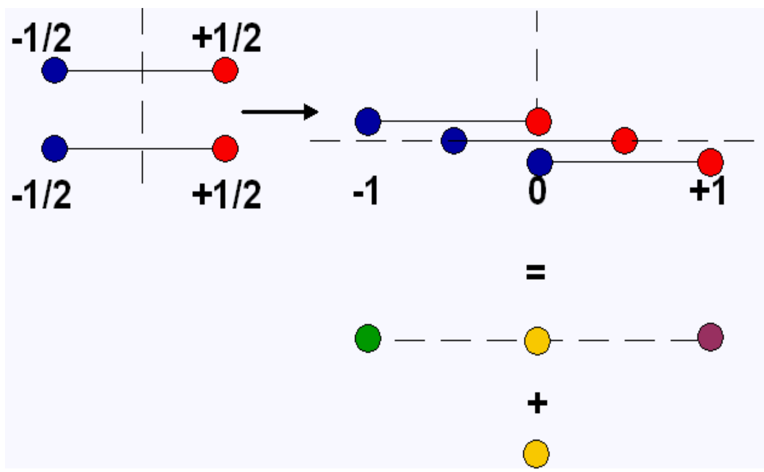
Answer (After a little group theory):

$$\mathbf{2} \otimes \mathbf{2} = \mathbf{1} \oplus \mathbf{3}$$

Answer (Graphical):

Center the segment carrying the 2 states of representation **2** *(1st nucleon) over the 2 states of representation* **2** *(2nd nucleon)*

$\rightarrow$ *Get a set of 4 states, decomposing into 2 sets of 1 and 3 states*



I-Spin Multiplets: Zoology

Amazingly *large* number of resonant states

$p,\ n$	P_{11}	****	$\Delta(1232)$	P_{33}	****
$N(1440)$	P_{11}	****	$\Delta(1600)$	P_{33}	***
$N(1520)$	D_{13}	****	$\Delta(1620)$	S_{31}	****
$N(1535)$	S_{11}	****	$\Delta(1700)$	D_{33}	****
$N(1650)$	S_{11}	****	$\Delta(1750)$	P_{31}	*
$N(1675)$	D_{15}	****	$\Delta(1900)$	S_{31}	**
$N(1680)$	F_{15}	****	$\Delta(1905)$	F_{35}	****
$N(1700)$	D_{13}	***	$\Delta(1910)$	P_{31}	****
$N(1710)$	P_{11}	***	$\Delta(1920)$	P_{33}	***
$N(1720)$	P_{13}	****	$\Delta(1930)$	D_{35}	***
$N(1900)$	P_{13}	**	$\Delta(1940)$	D_{33}	*
$N(1990)$	F_{17}	**	$\Delta(1950)$	F_{37}	****
$N(2000)$	F_{15}	**	$\Delta(2000)$	F_{35}	**
$N(2080)$	D_{13}	**	$\Delta(2150)$	S_{31}	*
$N(2090)$	S_{11}	*	$\Delta(2200)$	G_{37}	*
$N(2100)$	P_{11}	*	$\Delta(2300)$	H_{39}	**
$N(2190)$	G_{17}	****	$\Delta(2350)$	D_{35}	*
$N(2200)$	D_{15}	**	$\Delta(2390)$	F_{37}	*
$N(2220)$	H_{19}	****	$\Delta(2400)$	G_{39}	**
$N(2250)$	G_{19}	****	$\Delta(2420)$	$H_{3,11}$	****
$N(2600)$	$I_{1,11}$	***	$\Delta(2750)$	$I_{3,13}$	**
$N(2700)$	$K_{1,13}$	**	$\Delta(2950)$	$K_{3,15}$	**

Baryons

I=1/2 *I=3/2*

$L_{2J+1,2I+1}$ $L = S, P, D, \ldots$

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(400\text{–}1200)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\omega(782)$	$0^-(1^{--})$	$a_2(1750)$	$1^-(2^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	$X(1775)$	$1^-(?^{-+})$
• $a_0(980)$	$1^-(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $\phi(1020)$	$0^-(1^{--})$	$f_2(1810)$	$0^+(2^{++})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	$X(1910)$	$0^+(?^{?+})$
• $f_2(1270)$	$0^+(2^{++})$	$f_2(1950)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$	$X(2000)$	$1^-(?^{?+})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$f_0(2020)$	$0^+(0^{++})$
• $a_2(1320)$	$1^-(2^{++})$	• $a_4(2040)$	$1^-(4^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $f_4(2050)$	$0^+(4^{++})$
$h_1(1330)$	$?^-(1^{+-})$	$f_0(2060)$	$0^+(0^{++})$
$\pi_1(1400)$	$1^-(1^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $f_1(1420)$	$0^+(1^{++})$	$f_2(2150)$	$0^+(2^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$\rho(2150)$	$1^+(1^{--})$
$f_2(1430)$	$0^+(2^{++})$	$f_0(2200)$	$0^+(0^{++})$
• $\eta(1440)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $a_0(1450)$	$1^-(0^{++})$	$\eta(2225)$	$0^+(0^{-+})$
• $\rho(1450)$	$1^+(1^{--})$	$\rho_3(2250)$	$1^+(3^{--})$
• $f_0(1500)$	$0^+(0^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_1(1510)$	$0^+(1^{++})$	$f_4(2300)$	$0^+(4^{++})$
• $f_2'(1525)$	$0^+(2^{++})$	• $f_2(2340)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$\pi_1(1600)$	$1^-(1^{-+})$	$a_6(2450)$	$1^-(6^{++})$
$X(1600)$	$2^+(2^{++})$	$f_6(2510)$	$0^+(6^{++})$
$a_1(1640)$	$1^+(1^{++})$	$X(3250)$	$?^?(?^{??})$
$f_2(1640)$	$0^+(2^{++})$		
$\eta_2(1645)$	$0^+(2^{-+})$		
• $\omega(1650)$	$0^-(1^{--})$		
$X(1650)$	$0^-(?^{?-})$		
$a_2(1660)$	$1^-(2^{++})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

I=2 ???

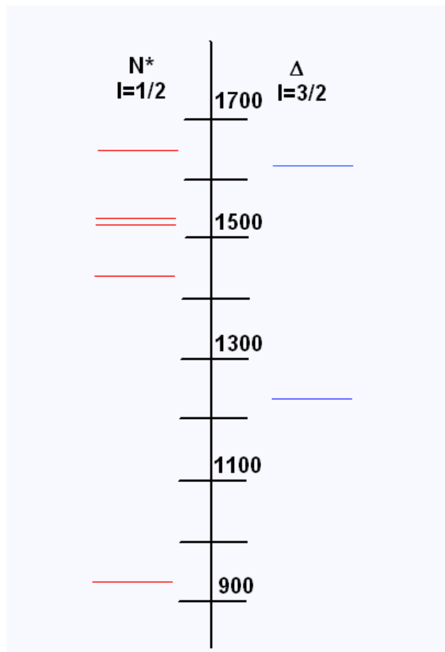
Mesons

I=0,1

Baryon Resonances Systematics

Two families of nucleon excited states: First, lightest states

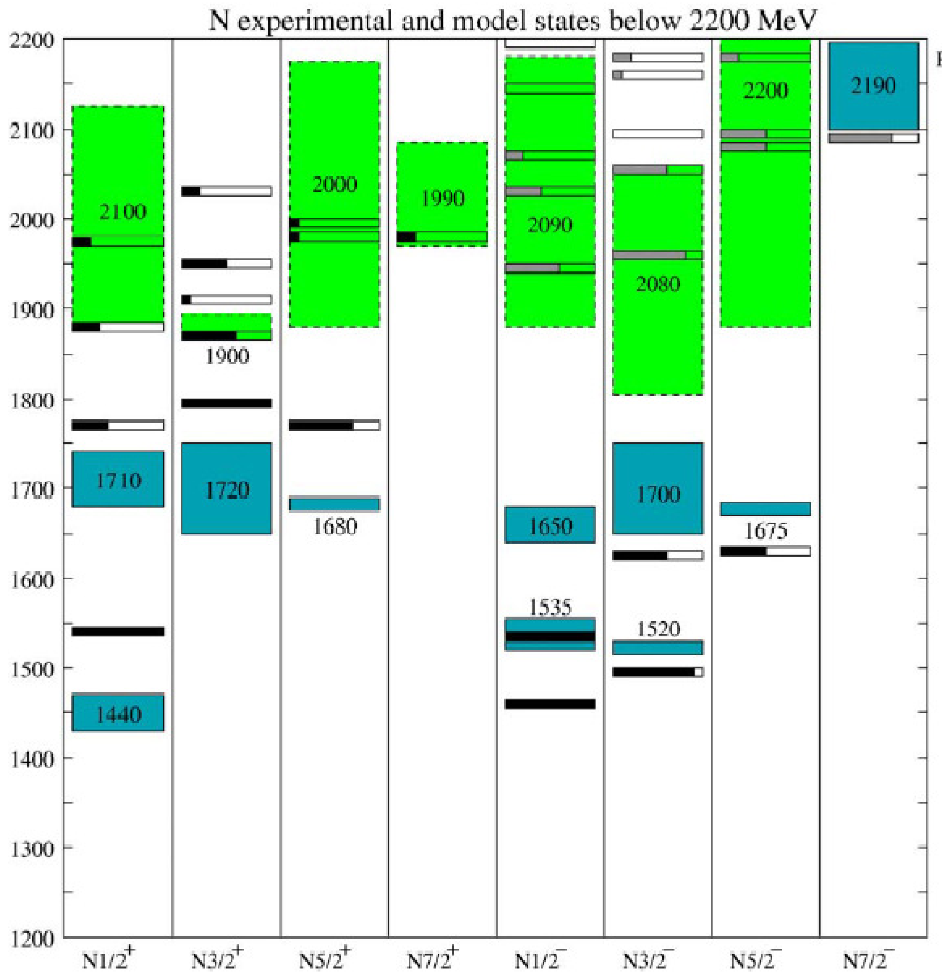
N* isospin =1/2



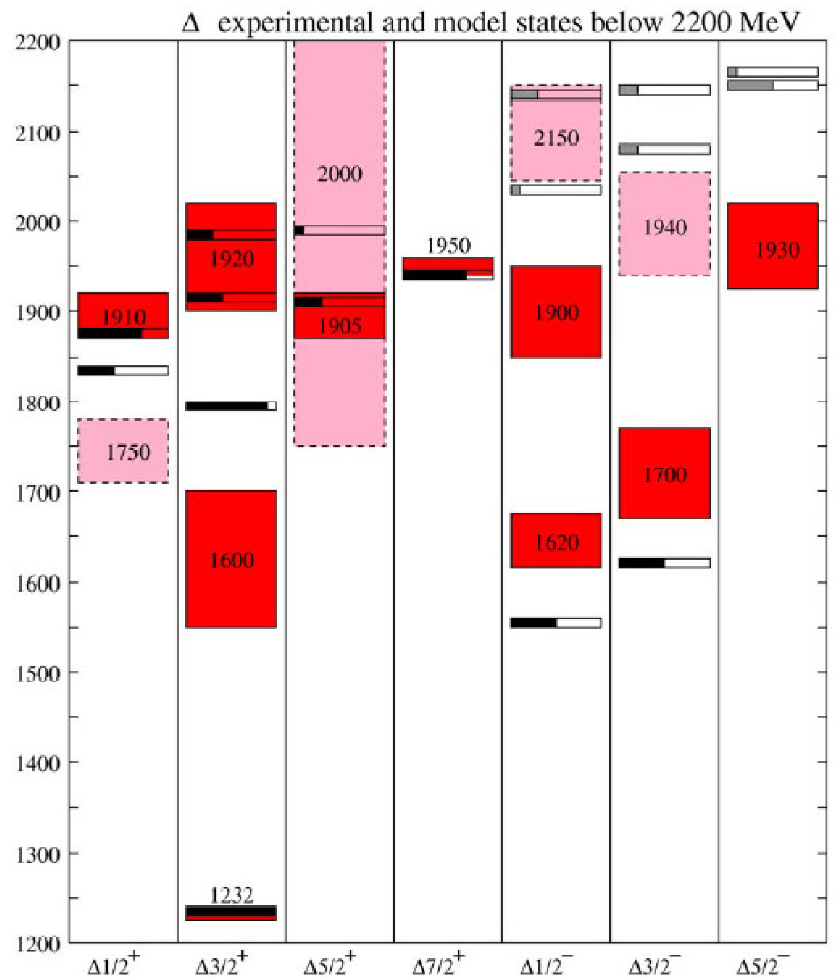
Δ isospin = 3/2

Many sub-families for each one (increasing *J*, parity + or -)

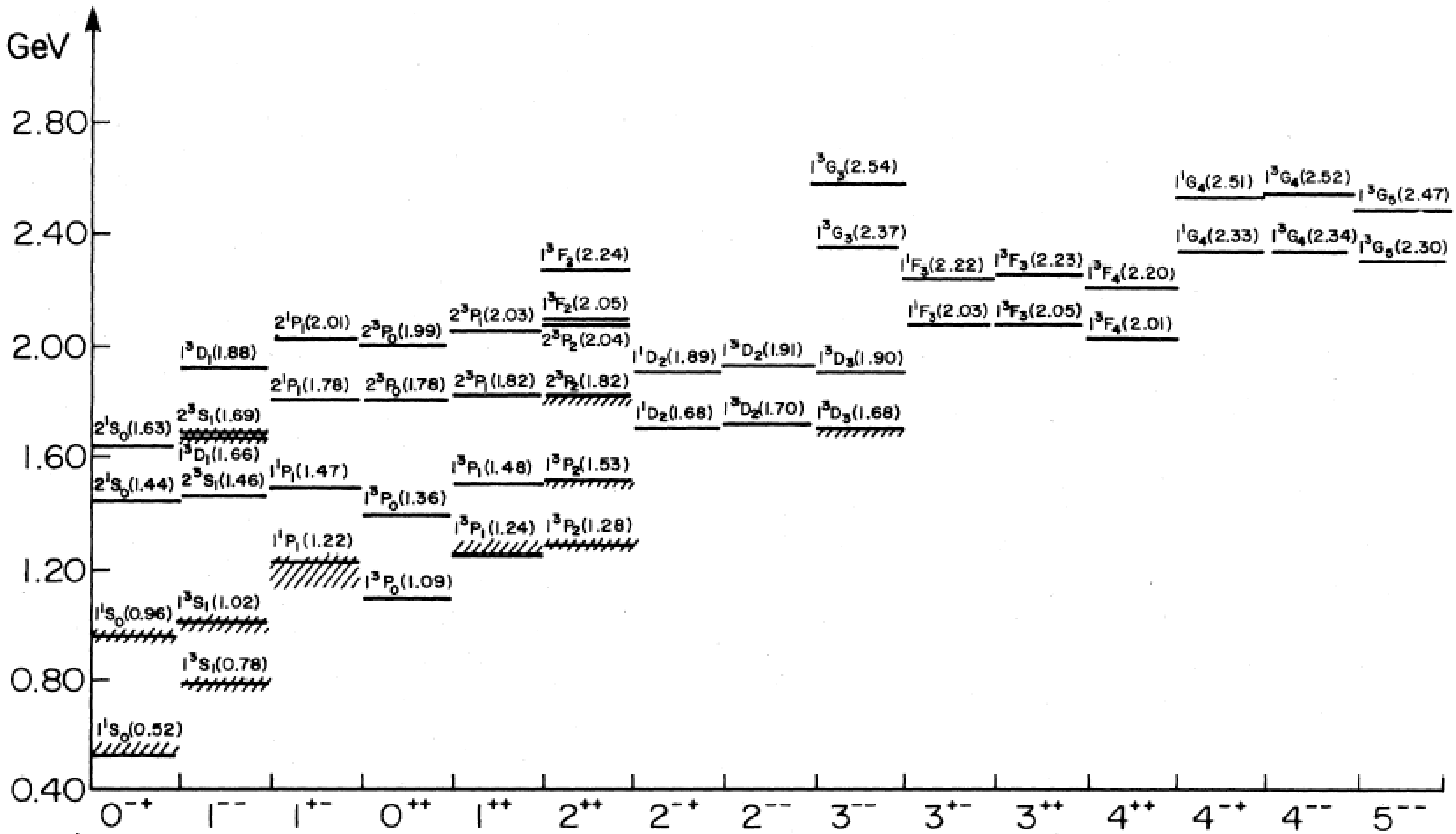
Non-strange Baryons – $I = 1/2$



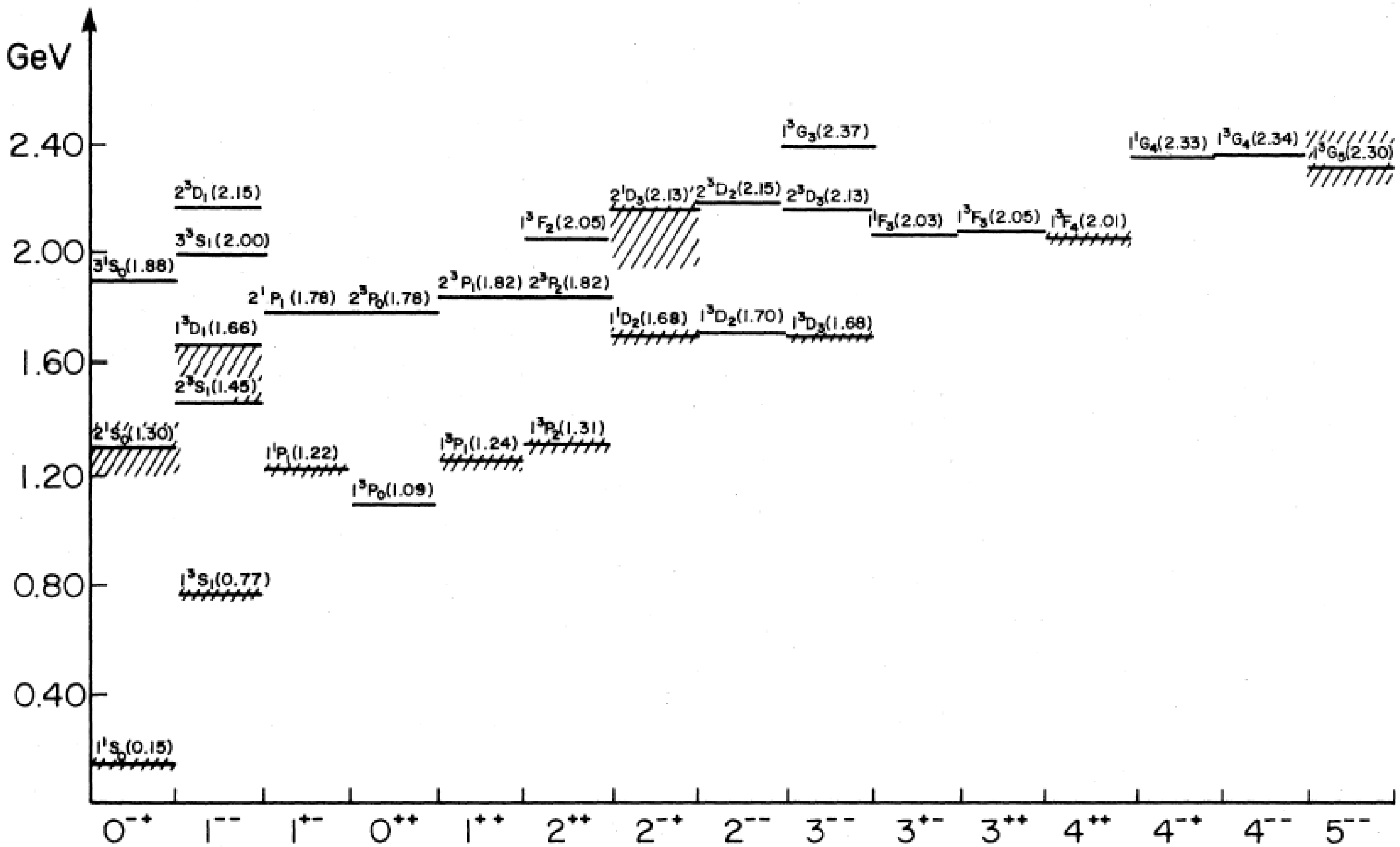
Non-strange Baryons – *I=3/2*



Non-Strange Mesons – *I=0*



Non-Strange Mesons – *I=1*



Gell-Mann – Nishijima Rule

B = Baryon number
Q = Charge in e units
I_3 = Isospin 3rd component

Empirical relationship for pions:

$$Q = I_3$$

Linking electromagnetic and strong properties of pions:
Electric charge as *3rd component* of isospin vector

Extend to nucleons:
$Q = I_3 + B/2$ Gell-Mann - Nishijima relation
More complicated properties:
Electric charge as both *isoscalar* and *3rd component of isovector*

Strangeness - I

Strange particles discovered in cosmic rays at the end of the ’40s, and then quicky observed at the first GeV accelerators

Why strange?

Large production cross section $\rightarrow$ *Like ordinary hadrons*
Long lifetime $\rightarrow$ *Like weak decays*

Understood as carriers of a new quantum number: *Strangeness*

Ordinary hadrons $S = 0$
Strange particles $S \# 0$

Strangeness conserved by strong, e.m. processes, violated by weak
Explain funny behavior, also predicting *associated production* to guarantee *S* conservation in strong & EM processes:

Strange particles always produced in pairs

Strangeness - II

For strong processes, *S* similar to electric charge and to baryon or lepton numbers
But:

S not absolutely conserved

S not the source of a physical field

Large variety of strange particles, both baryons and mesons, including many strange resonances

Generalize Gell-Mann Nishijima relation to

$$Q = I_3 + \frac{B+S}{2} = I_3 + \frac{Y}{2}$$

$$Y = B + S \quad \text{Hypercharge}$$

The Lightest Strange Particles

Mesons

I_3	S=+1	S=-1
+1/2	K^+	K^0
-1/2	$\bar{K}^0$	K^-

Spin 0

I_3	S=+1	S=-1
+1/2	K^{*+}	$\bar{K}^{*0}$
-1/2	K^{*0}	K^{*-}

Spin 1

I_3	S	name
0	-1	Λ^0
+1,0,-1	-1	$\Sigma^+,\Sigma^-,\Sigma^0$
+1/2,-1/2	-2	Ξ^0,Ξ^-
0	-3	Ω^-

Baryons

I_3	S	name
0	+1	$\bar{\Lambda}^0$
+1,0,-1	+1	$\bar{\Sigma}^+,\bar{\Sigma}^0,\bar{\Sigma}^-$
+1/2,-1/2	+2	$\bar{\Xi}^0,\bar{\Xi}^-$
0	+3	$\bar{\Omega}^-$

Antibaryons

Isospin of Strange Particles

Isospin conservation in

$$\pi^- + p \to \pi^- + p$$

leads in a natural way to extend to virtual states like

$$\pi^- + p \to \left(K^0 + \Lambda^0\right)^* \to \pi^- + p$$

→Strange particles should group into I-spin multiplets.

Λ^0 only observed as a neutral state $\to$ Singlet , $I = 0$

Observe 3 charge states for K: Triplet?

$\pi^- + p : I = 1/2, 3/2 \to K$ must be $I = 1/2, 3/2$

Quartets not observed $\to$ 2 Doublets! Predict *two* neutral *K* states, with opposite *S*

Would imply charge +2

$$\pi^- + p \to K^0 + \Lambda^0$$

$$p + \overline{p} \to K^0 + \overline{K}^0$$

Must be different particles!

Bubble Chambers: Particle Zoology

Example: Historical Picture

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

$$K^0 \to \pi^+ + \pi^-$$

$$K^+ \to \pi^+ + \pi^0 \,(unseen)$$

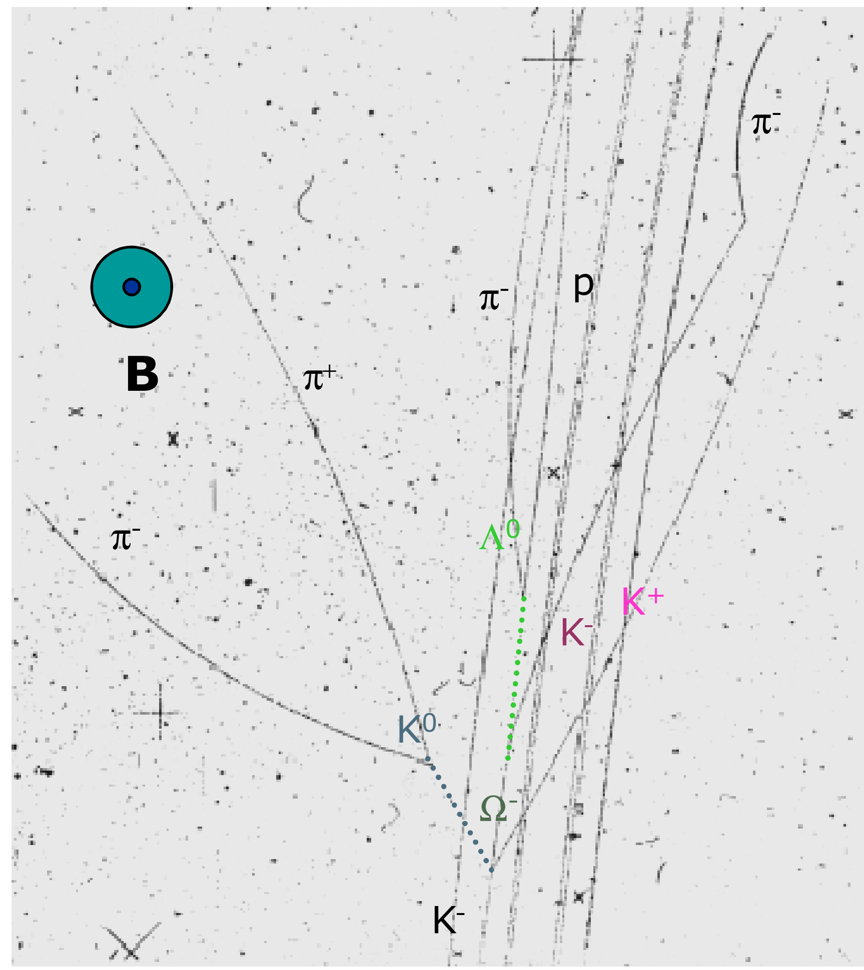
$$\Omega^- \to \Lambda^0 + K^-$$

$$\Lambda^0 \to p + \pi^-$$

$$K^- \to \pi^- + \pi^0 \,(unseen)$$

Beam momentum 4.2 GeV

Magnetic field 2 T



Hyperon Beam & Spectrometer - I

FNAL – ’70s Beam & Detector of Hyperon Experiment

400 GeV p beam
extracted from accelerator

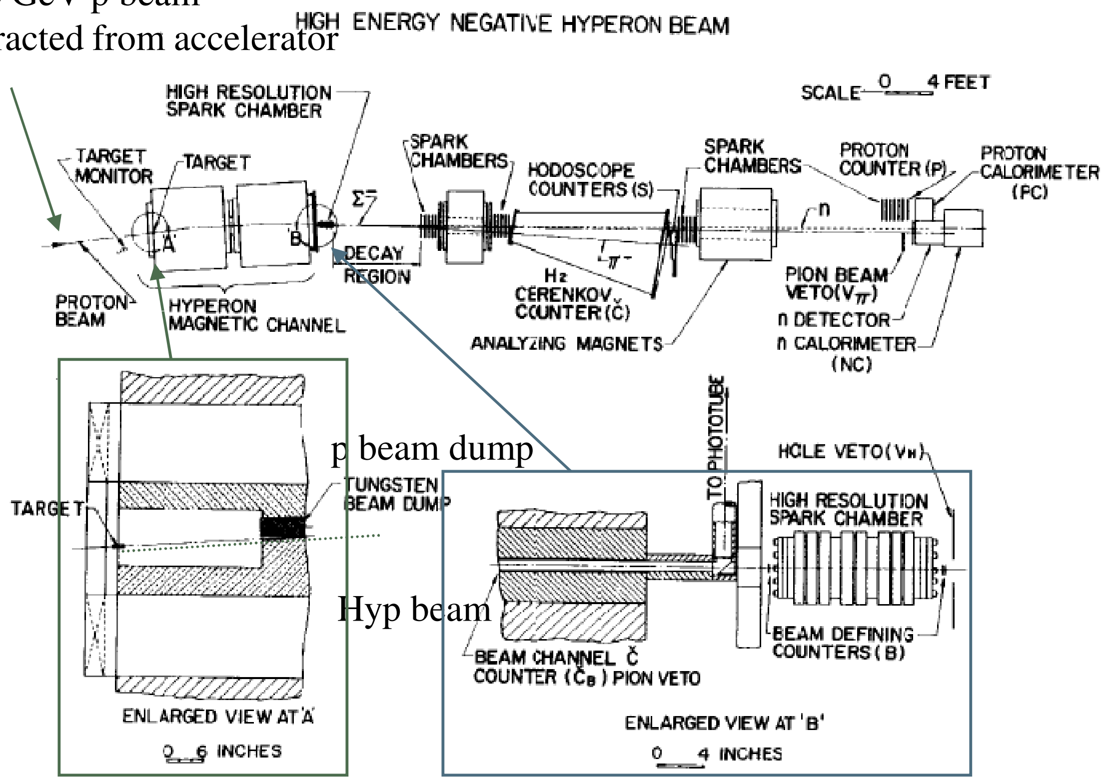


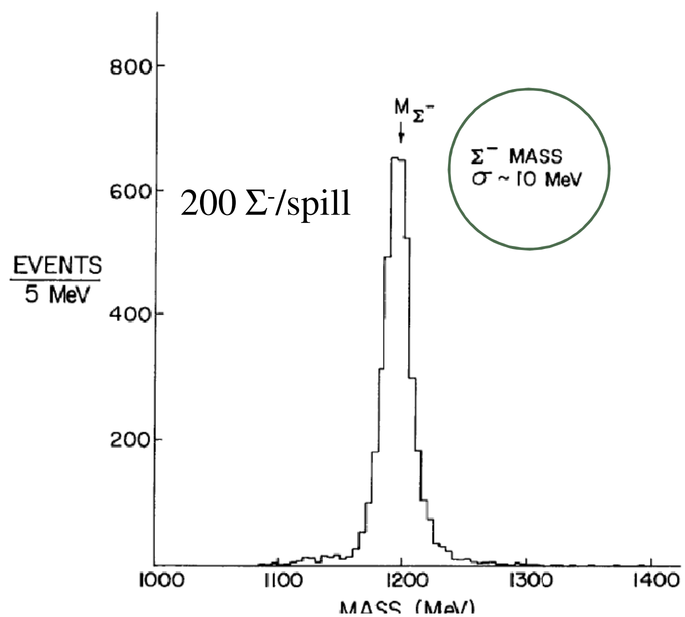
Fig. 1

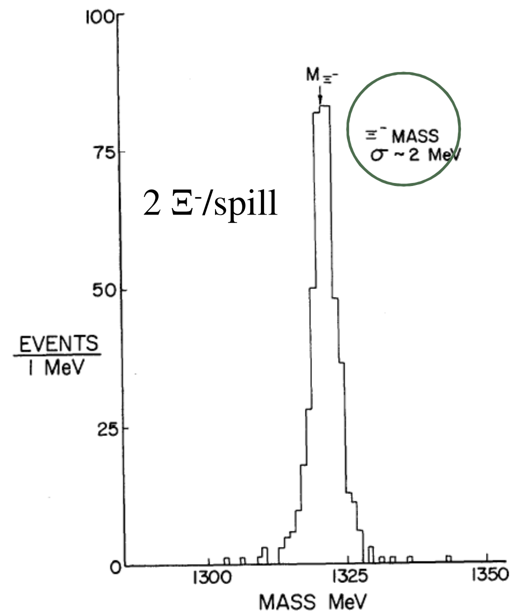
Hyperon Gymnastics

Hyperon Beam & Spectrometer - II

Reconstruct decays: $\Sigma^- \to n + \pi^-, \quad \Xi^- \to \Lambda^0 + \pi^-$

π: Identification (Threshold Cherenkov) + Magnetic Analysis
n: Calorimeter
p: Identification (Cherenkov *p* Veto) + Magnetic Analysis + Calorimeter
$\Lambda^0 \to p + \pi$: Identification + Magnetic Analysis





Particle Id: Cherenkov - I

Fast, charged particle passing through a dielectric medium

Cherenkov radiation emitted for $\beta > \frac{1}{n}$, n refractive index

Main features:

Emission angle:

$$\cos\theta_c = \frac{1}{\beta n}$$ Cherenkov angle

For ultrarelativistic particles:

$$\lim_{\beta\to 1}(\cos\theta_c) = \frac{1}{n}$$ Asymptotic angle

Spectrum:

Representative radiators

Medium	***n***	***θ_{min} deg***	***$P_{thresh}(p)$ GeV***	***N_{ph} $eV^{-1}cm^{-1}$***
Air	**1.00028**	**1.36**	**5.9**	**0.21**
Isobutane	**1.00217**	**3.77**	**2.12**	**0.94**
Aerogel	**1.0065**	**6.51**	**1.3**	**4.7**
Water	**1.33**	**41.2**	**0.16**	**160.8**
Quartz	**1.46**	**46.7**	**0.13**	**196.4**

$1/\lambda^2$ spectrum: Blue/Near UV *very* important…

$$\frac{d^2N}{dxd\lambda} = 2\pi\alpha z^2 \frac{1}{\lambda^2}\sin^2\theta_c \quad photons/cm^2,$$ z particle charge in e units

$$\frac{d^2N}{dxdE} = \frac{\alpha}{\hbar c} z^2 \sin^2\theta_c \approx 365 z^2 \sin^2\theta_c \quad photons/(cm\cdot eV)$$

Number of photons/cm small…

Particle Id: Cherenkov - II

Translate light signal into an electric charge: *Photomultiplier*, or similar

Typical result with a PM (E = Cherenkov photon energy):

$$N_{pe} \approx 365 \int_{E_{\min}}^{E_{\max}} \varepsilon_{coll}(E)\varepsilon_{\det}(E)\sin^2\theta_c(E)\,dE$$ N. of photoelectrons/cm obtained

Collection efficiency

Conversion efficiency

Cherenkov angle depending on E: $\cos\theta_c = \frac{1}{\beta n(\lambda)} = \frac{1}{\beta n(E)}$ Dispersion of refractive index

Typically:

$N_{pe} \le 100 \sin^2\theta_c$ Photoelectrons/cm

Threshold counter

$$\beta > \frac{1}{n} \to \frac{p}{E} > \frac{1}{n} \to \frac{p}{\sqrt{p^2+m^2}} > \frac{1}{n} \to p^2 > \frac{1}{n^2}\left(p^2+m^2\right)$$

$$\to p^2\left(1-\frac{1}{n^2}\right) > \frac{m^2}{n^2} \to p^2 > \frac{m^2}{n^2-1} \to p > \frac{m}{\sqrt{n^2-1}}$$ Threshold momentum

Can discriminate among different masses with the same momentum

The Strange Zoo

Baryons, *S=-1,-2,-3* (Antibaryons not shown)

Λ	P_{01}	****
$\Lambda(1405)$	S_{01}	****
$\Lambda(1520)$	D_{03}	****
$\Lambda(1600)$	P_{01}	***
$\Lambda(1670)$	S_{01}	****
$\Lambda(1690)$	D_{03}	****
$\Lambda(1800)$	S_{01}	***
$\Lambda(1810)$	P_{01}	***
$\Lambda(1820)$	F_{05}	****
$\Lambda(1830)$	D_{05}	****
$\Lambda(1890)$	P_{03}	****
$\Lambda(2000)$		*
$\Lambda(2020)$	F_{07}	*
$\Lambda(2100)$	G_{07}	****
$\Lambda(2110)$	F_{05}	***
$\Lambda(2325)$	D_{03}	*
$\Lambda(2350)$	H_{09}	***
$\Lambda(2585)$		**
Ω^-		****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

Ξ^0	P_{11}	****
Ξ^-	P_{11}	****
$\Xi(1530)$	P_{13}	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	D_{13}	***
$\Xi(1950)$		***
$\Xi(2030)$		***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*

Σ^+	P_{11}	****
Σ^0	P_{11}	****
Σ^-	P_{11}	****
$\Sigma(1385)$	P_{13}	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	D_{13}	*
$\Sigma(1620)$	S_{11}	**
$\Sigma(1660)$	P_{11}	***
$\Sigma(1670)$	D_{13}	****
$\Sigma(1690)$		**
$\Sigma(1750)$	S_{11}	***
$\Sigma(1770)$	P_{11}	*
$\Sigma(1775)$	D_{15}	****
$\Sigma(1840)$	P_{13}	*
$\Sigma(1880)$	P_{11}	**
$\Sigma(1915)$	F_{15}	****
$\Sigma(1940)$	D_{13}	***
$\Sigma(2000)$	S_{11}	*
$\Sigma(2030)$	F_{17}	****
$\Sigma(2070)$	F_{15}	*
$\Sigma(2080)$	P_{13}	**
$\Sigma(2100)$	G_{17}	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Mesons, *S*=±*1*

•	K^-	$1/2(0^-)$
•	K^0	$1/2(0^-)$
•	K^0_S	$1/2(0^-)$
•	K^0_L	$1/2(0^-)$
	$K_0^*(800)$	$1/2(0^+)$
•	$K^*(892)$	$1/2(1^-)$
•	$K_1(1270)$	$1/2(1^+)$
•	$K_1(1400)$	$1/2(1^+)$
•	$K^*(1410)$	1/2(1)
•	$K_0^*(1430)$	$1/2(0^+)$
•	$K_2^*(1430)$	$1/2(2^+)$
	$K(1460)$	$1/2(0^-)$
	$K_2(1580)$	$1/2(2^-)$
	$K(1630)$	$1/2(?^?)$
	$K_1(1650)$	$1/2(1^+)$
•	$K^*(1680)$	1/2(1)
•	$K_2(1770)$	$1/2(2^-)$
•	$K_3^*(1780)$	$1/2(3^-)$
•	$K_2(1820)$	$1/2(2^-)$
	$K(1830)$	$1/2(0^-)$
	$K_0^*(1950)$	$1/2(0^+)$
	$K_2^*(1980)$	$1/2(2^+)$
•	$K_4^*(2045)$	$1/2(4^+)$
	$K_2(2250)$	$1/2(2^-)$
	$K_3(2320)$	$1/2(3^+)$
	$K_5^*(2380)$	$1/2(5^-)$
	$K_4(2500)$	$1/2(4^-)$
	$K(3100)$	$?^?(?^{??})$

Higher Symmetry

Experimental evidence for several 'multiplets of multiplets'

$J^P=0^-$

I	S=+1	S=0	S=-1
0		$\eta,\eta^{'}$	
1/2	K		$\bar{K}$
1		π	

$J^P=1^-$

I	S=+1	S=0	S=-1
0		ω,φ	
1/2	K^*		$\bar{K}^*$
1		ρ	

$J^P=2^+$

I	S=+1	S=0	S=-1
0		f_0, f_1	
1/2	K^{**}		$\bar{K}^{**}$
1		a_2	

Mesons

$J^P=1/2^+$

I	S=-2	S=-1	S=0
0		Λ^0	
1/2	Ξ		N
1		Σ	

$J^P=3/2^+$

I	S=-3	S=-2	S=-1	S=0
0	Ω^-			
1/2		Ξ^*		
1			Σ^*	
3/2				Δ

Baryons

Remember: Each square is a *I-spin multiplet,* with size (2I+1)
Total of 45 particle states in this page!

SU(3) - I

Try to find a larger group to encompass both strangeness and isospin into a unified symmetry scheme.

Requirements:

2 commuting generators, since both S and I_3 are defined within any observed supermultiplet

NB SU(2) has just one, I_3

Multiplet structure matching experimental data

SU(3) - II

Take *SU(3)* as candidate to extend *SU(2):*

Group of unitary, unimodular 3x3 matrices

9 complex parameters $\rightarrow$ 18 real parameters

9 unitary conditions: $\left.\begin{matrix} UU^{\dagger} = 1 \\ \left(U^{\dagger}\right)_{ij} = U^{*}_{ji} \end{matrix}\right\} \rightarrow \sum_{j=1}^{3} a_{ij} a^{*}_{jk} = \delta_{ik}, \quad i,k = 1,..,3$

1 unimodularity condition: $\det U = 1$

$\rightarrow 18 - 10 = 8$ free, real parameters

$SU(3)$ - III

As usual, for any unitary matrix

$$U = e^{iH}, \quad H \text{ Hermitian}$$

$$\det U = 1 \rightarrow \det e^{iH} = 1 \rightarrow e^{itr(H)} = 1 \rightarrow tr(H) = 0$$

8 parameters $\rightarrow$ 8 generators

Generalize Pauli matrices to *Gell-Mann matrices*

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix},$$

$$\lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

SU(3) - IV

Commutators:

$\left[\lambda_i, \lambda_j\right] = f_{ijk}\lambda_k$, $\quad f_{ijk}$ structure constants

Two diagonal generators, l_3 and l_8

→ *Rank 2 group*

→ 2 invariant functions of generators

Quadratic: $$C^{(2)} = \sum_{i,j=1}^{8} \delta_{ij}\lambda_i\lambda_j$$

Cubic: $$C^{(3)} = \sum_{i,j,k=1}^{8} f_{ijk}\lambda_i\lambda_j\lambda_k$$

$F_i \equiv \frac{\lambda_i}{2}$ Definition

Identify: $\begin{cases} I_3 = F_3 & \text{Isospin 3rd component} \\ Y = \frac{2}{\sqrt{3}} F_8 & \text{Hypercharge} \end{cases}$

Compare to *SU(2):*

$\left[\sigma_i, \sigma_j\right] = i\varepsilon_{ijk}\sigma_k$

One diagonal generator, σ_3

→ *Rank 1 group*

→ *1* invariant function of generators

Quadratic: $$C^{(2)} = \sum_{i,j=1}^{3} \delta_{ij}\sigma_i\sigma_j$$

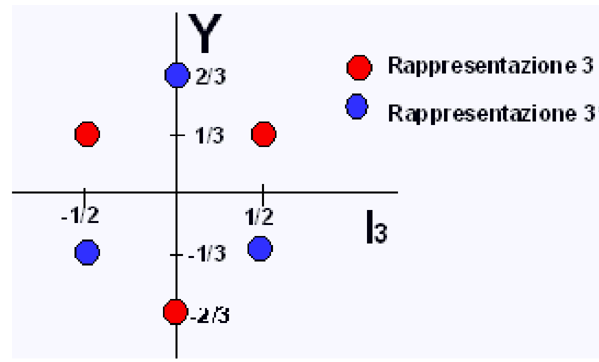
SU(3) Surprises

Fundamental representation (3 x 3 matrices): ***3***

Find eigenvalues & eigenvectors for **3**:

$$\begin{pmatrix}1\\0\\0\end{pmatrix} \to \begin{cases} I_3 = \frac{1}{2} \\ Y = \frac{1}{3} \end{cases}; \quad \begin{pmatrix}0\\1\\0\end{pmatrix} \to \begin{cases} I_3 = -\frac{1}{2} \\ Y = \frac{1}{3} \end{cases}; \quad \begin{pmatrix}0\\0\\1\end{pmatrix} \to \begin{cases} I_3 = 0 \\ Y = -\frac{2}{3} \end{cases}$$

$Y = B + S$



$\to$ 3 independent base states

$\to I_3, Y$ eigenvalues not symmetrical wrt origin

$\to$ Conjugate representation: **3*** different from **3**

$\to$ For both **3**, **3*** hypercharge eigenvalues fractionary

$\to Q = I_3 + Y/2$ fractionary!!!

$SU(3)$ Multiplets - I

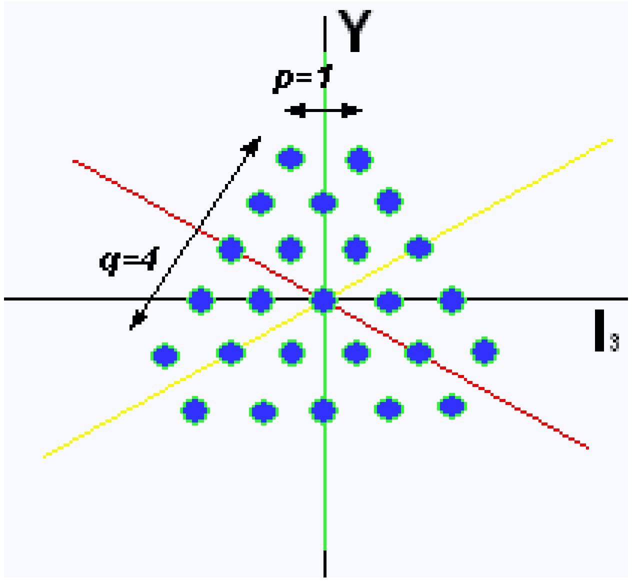
States identified by Y, I_3 eigenvalues
$\rightarrow$Points in a plane

Hexagonal/Triangular symmetry

Specified by *2* integers (p,q)

Multiplicity (i.e. size)

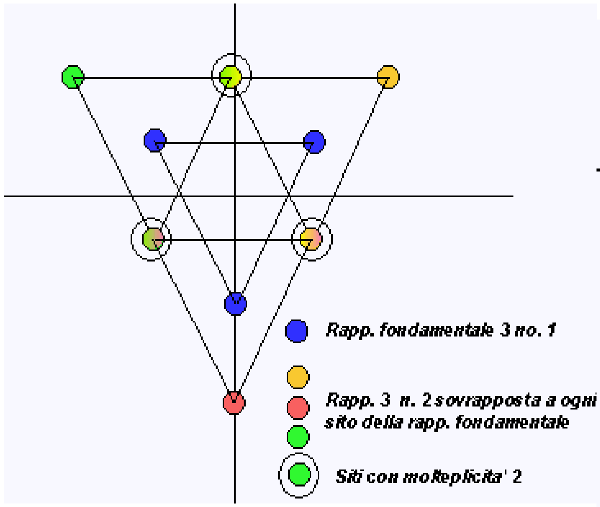
$$n = \frac{1}{2}(p+1)(q+1)(p+q+2)$$

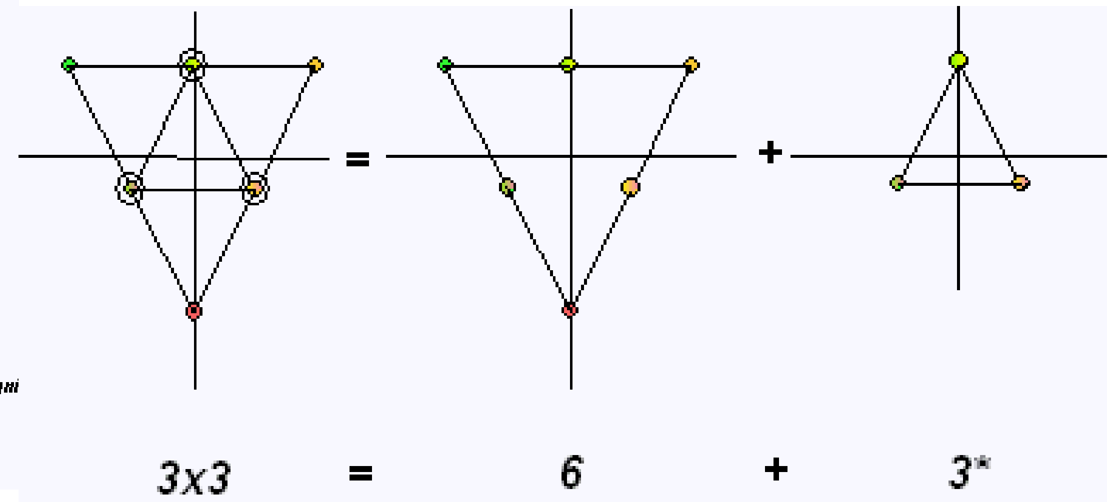


Multiplet *(1,4)*
Frequently indicated by ***n****=35*

SU(3) Multiplets - II

Products and decomposition into irr.rep.:
Proceed graphically as for *SU(2)*

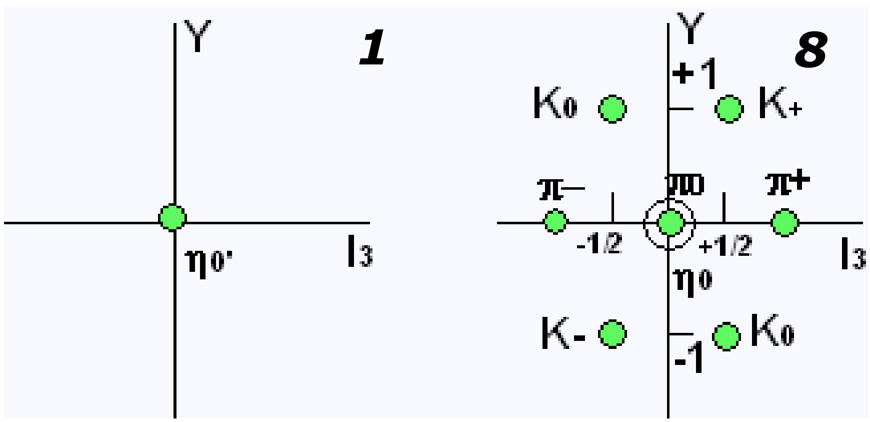




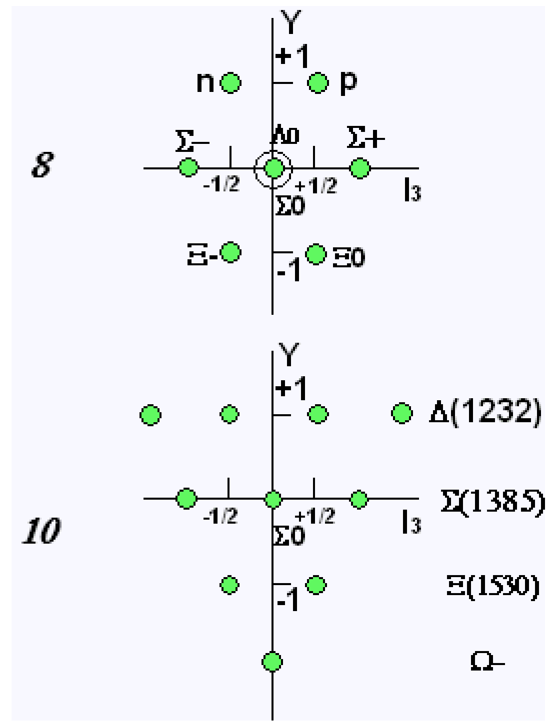
The Eightfold Way

All the hadronic multiplets nicely fit some SU(3) representation
No hadron found which does not fit

Mesons $J^{PC}=0^{-+}$



Baryons $J^P=1/2^+,3/2^+$



The Hard Facts: *SU(3)* Breaking

$J^P=0^-$

I	S=-1	S=0	S=+1
0		$\eta(547), \eta'(958)$	
1/2	$\bar{K}(496)$		$K(496)$
1		$\pi(137)$	

$J^P=1^-$

I	S=-1	S=0	S=+1
0		$\omega(782), \varphi(1020)$	
1/2	$\bar{K}^*(892)$		$K^*(892)$
1		$\rho(770)$	

$J^P=2^+$

I	S=-1	S=0	S=+1
0		$f_2(1270), f_2'(1525)$	
1/2	$\bar{K}^{**}(1430)$		$K^{**}(1430)$
1		$a_2(1320)$	

$J^P=1/2^+$

I	S=-2	S=-1	S=0
0		$\Lambda^0(1116)$	
1/2	$\Xi(1317)$		$N(938)$
1		$\Sigma(1192)$	

$J^P=3/2^+$

I	S=-3	S=-2	S=-1	S=0
0	$\Omega^-(1672)$			
1/2		$\Xi^*(1530)$		
1			$\Sigma^*(1385)$	
3/2				$\Delta(1232)$

As before, but including masses: *SU(3)* is not an exact symmetry

Mass differences within a multiplet are large, typ. $\Delta m/m \sim 10\text{-}20\%$

SU(3) Breaking: Mass Formulas - I

Since SU(3) is a broken symmetry, try to find a sensible breaking scheme

Take an *effective Hamiltonian*:

Part SU(3)-Invariant + Part non SU(3)-Invariant

$$m_{hadron} \simeq \langle hadron | H_S | hadron \rangle, \quad H_S = H_0 + H'$$

$$\langle a | H_s | a \rangle \rightarrow \underbrace{\langle a | U^{-1}}_{\substack{SU(3)-transformed \\ state}} \; H \; \underbrace{U | a \rangle}_{\substack{SU(3)-transformed \\ state}}$$

$$\rightarrow \langle a | U^{-1} (H_0 + H') U | a \rangle = \langle a | U^{-1} H_0 U | a \rangle + \langle a | U^{-1} H' U | a \rangle$$

$$H_0: \text{ invariant } \rightarrow U^{-1} H_0 U = H_0$$

$$H': \text{ non invariant } \rightarrow U^{-1} H' U \neq H'$$

$$\rightarrow \langle a | H | a \rangle = \langle a | U^{-1} H_0 U | a \rangle + \langle a | U^{-1} H' U | a \rangle = \langle a | H_0 | a \rangle + \langle a | U^{-1} H' U | a \rangle$$

Must guess SU(3) properties of *H’*

SU(3) Breaking: Mass Formulas - II

Since the largest breaking concerns strange particles, suppose

$\rightarrow H' \propto F_8 \propto Y$

Reminder: $I_3 = F_3,\ Y = \frac{2}{\sqrt{3}} F_8$

According to *SU(3)* algebra:

Gell-Mann Okubo mass formula

$$\langle a | H' | a \rangle \propto \langle a | F_8 | a \rangle \propto A + BY + C\left[Y^2/4 - I\left(I+1\right)\right]$$

$$m\left(Y, I\right) = m_0 + bY + C\left[Y^2/4 - I\left(I+1\right)\right]$$

A,B,C: constants, rep. dependent

$SU(3)$ Breaking: Mass Formulas - III

S = -3 decuplet member not observed.
What is the mass?

Take mass differences between decuplet members:

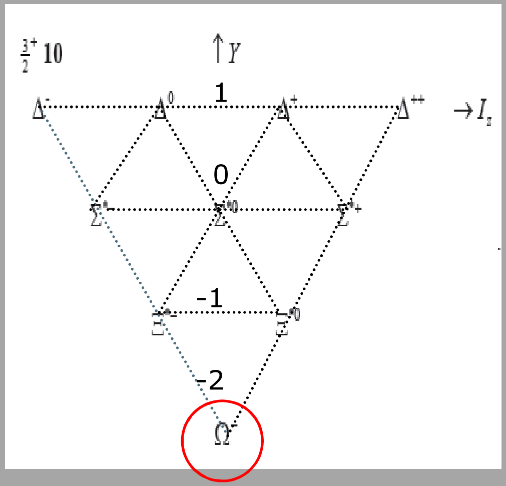
$$\Delta m_{ij} = m_i - m_j = b\left(\Delta Y\right)_{ij} + C\left[\left(Y_i^2 - Y_j^2\right)/4 - \left(I_i\left(I_i+1\right) - I_j\left(I_j+1\right)\right)\right]$$

From $\Delta(1232)$, $\Sigma^*(1385)$, $\Xi^*(1530)$:

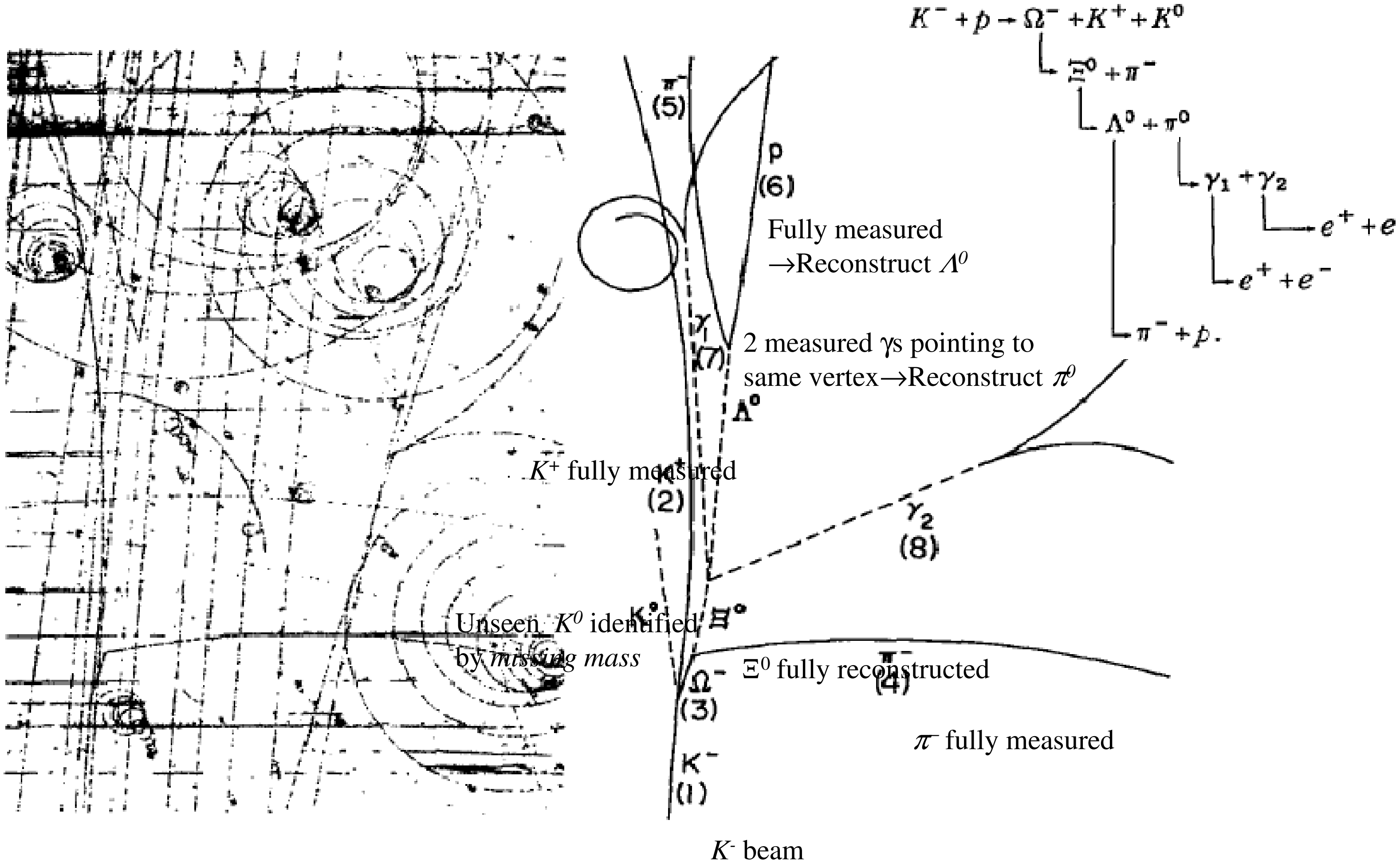
$$m_\Sigma - m_\Delta \approx m_\Xi - m_\Sigma \approx 150 \;\; MeV$$

$\rightarrow$ Predict missing $S = \text{-}3,\; J = 3/2$ decuplet baryon

Named Ω^-, predicted mass $m_\Omega \simeq 1672 \; MeV$



The Ω^- Discovery at BNL



$\rightarrow$ Get $M_{\Omega^-} = 1675\ MeV$!