THREE QUARKS: u, d, s

Precursor 1: Sakata Model

Precursor 2: Eightfold Way, Discovery of Ω^-

Quark Model: first three quarks and three colors

Search for free quarks

Static evidence for quarks: baryon magnetic moments

Early dynamic evidence:

- **πN and pN cross sections**
- **$R = \sigma_{ee \to hadrons} / \sigma_{ee \to \mu\mu}$**
- **Deep Inelastic Scattering (DIS) and partons**
- **Jets**

Sakata Model

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

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

Mesons (B=0):

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

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

Baryons (B=1):

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

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

S=-3 NOT possible

Resonances (B=1):

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

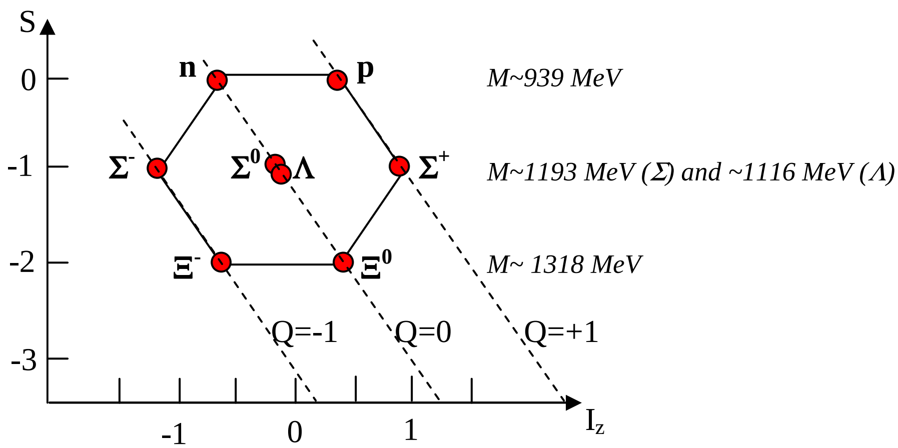
Sakata Model was the first attempt to come up with some plausible internal structure that would allow systemizing the emerging zoo of hadrons. Retrospectively, it was a precursor of the Quark Model to be discussed in the next lecture. However, the model was giving completely wrong magnetic moments and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

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

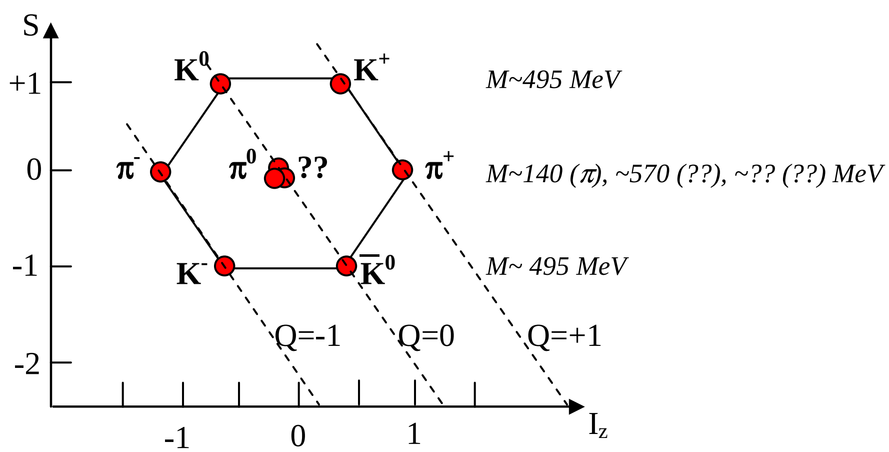
Eightfold Way

1961 **M. Gell-Mann** and **Y. Ne'eman** (independently a few months later) proposed a scheme that would put the jungle of particles in some sort of order, a la Mendeleyev 's Periodic Table. The scheme was based on properties of SU(3) group symmetries without appealing to any internal structure.

The term for this particle organization, "Eightfold Way", was coined by Gell-Mann after a noble eightfold way in Buddhism: one should walk through his/her life in compliance with the eight commandments of the Buddhism Religion. Gell-Mann enriched the high energy physics with such somewhat extravagant terms as strangeness, quarks, eightfold way, Ω^- (the last), …



Spin ½ Baryons



$J^P=0^-$ Mesons

** Predicted a new meson with mass of 570 MeV

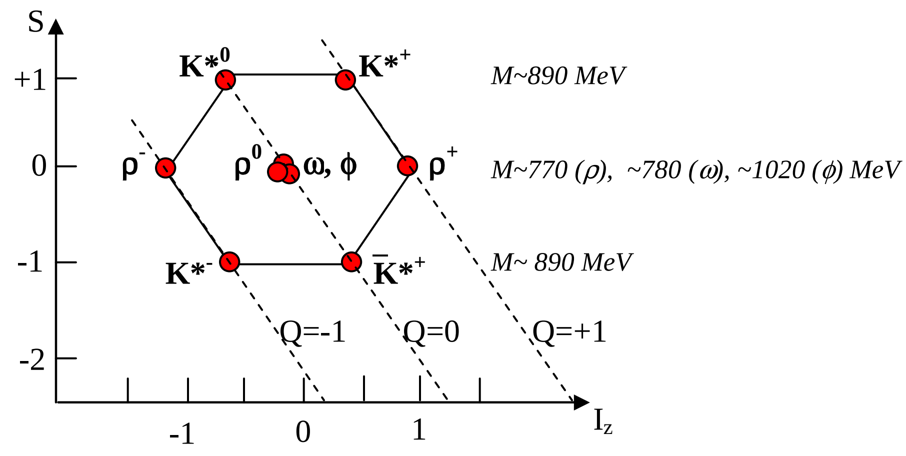
→ Particle was found (η) in Nov 1961 by Alvarez in $\pi^+ d \to pp\pi^+\pi^-\pi^0$ as a resonance in $(\pi^+\pi^-\pi^0)$-system with the invariant mass of 550 MeV.

** Note: there is one more meson with quantum numbers of π^0 and η (also, predicted by Sakata model): η'. Although it does not belong to this octet and should stand by itself as a singlet, it nevertheless is often put right next to π^0 and η). Its mass ~960 MeV.

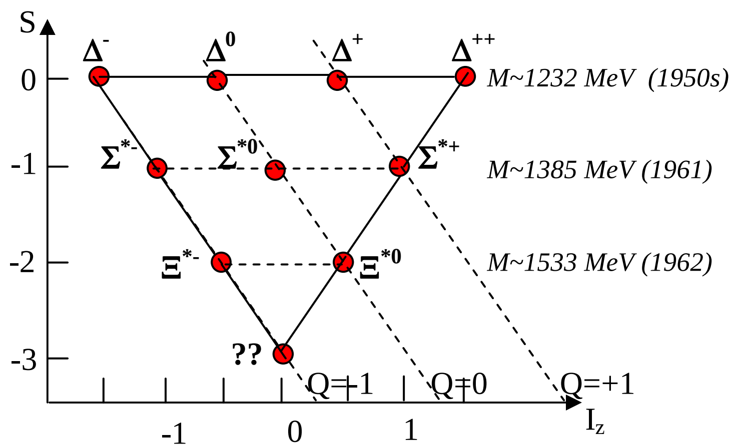
** Predicted that Ξ baryons would have spin 1/2

→ Confirmed in 1963

Extending Eightfold Way to Resonances



$J^P=1^-$ Meson Resonances
(all discovered by 1961)



Spin 3/2 Baryon Resonances

** Nucleon resonances with positive Strangeness did not fit the picture and were not seen…
** Predicted a new doublet of Ξ* resonances with S=-2 and one more resonance with S=-3 (???)

1962 Discovery of Ξ* resonance with mass ~1530 MeV is announced at the conference

1962 **Gell-Mann and Ne'eman** right at the same conference
predicted a new particle and wrote down all its properties:

Name = Ω^- (*Omega* would mean that the particle was the last in the decuplet)
Mass ≈ 1680 MeV (note that masses of Δ, Σ* and Ξ* are about equidistant, ~150 MeV)
Charge = -1
Spin = 3/2
Strangeness = -3
Lifetime ~10^{-10} s (note that it does not have a corresponding spin-1/2 with S=-3 that it could decay to via a strong force as all other resonances in this decuplet would do)
Decay modes: $\Xi^0\pi^-$ and $\Xi^-\pi^0$
Isospin = 0 (no charge-partners of similar mass)

Discovery of Ω^-

1964 Ω- is discovery at AGS accelerator in Brookhaven. CERN finds a similar event a few months later. Its mass is 1672 MeV.

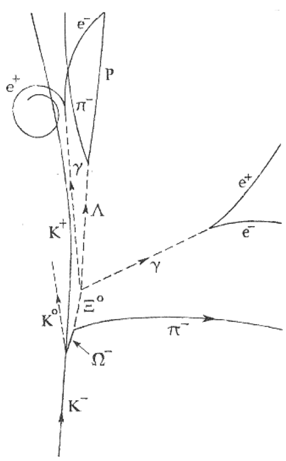
$K^- \; p \rightarrow \Omega^- \; K^+ \; K^0$

$\quad \hookrightarrow \Xi^0 \; \pi^-$

$\quad\quad \hookrightarrow \Lambda \; \pi^0$

$\quad\quad\quad \pi^0 \hookrightarrow 2\gamma \rightarrow 2\,(e^+e^-)$

$\quad\quad\quad \Lambda \hookrightarrow p\,\pi^-$



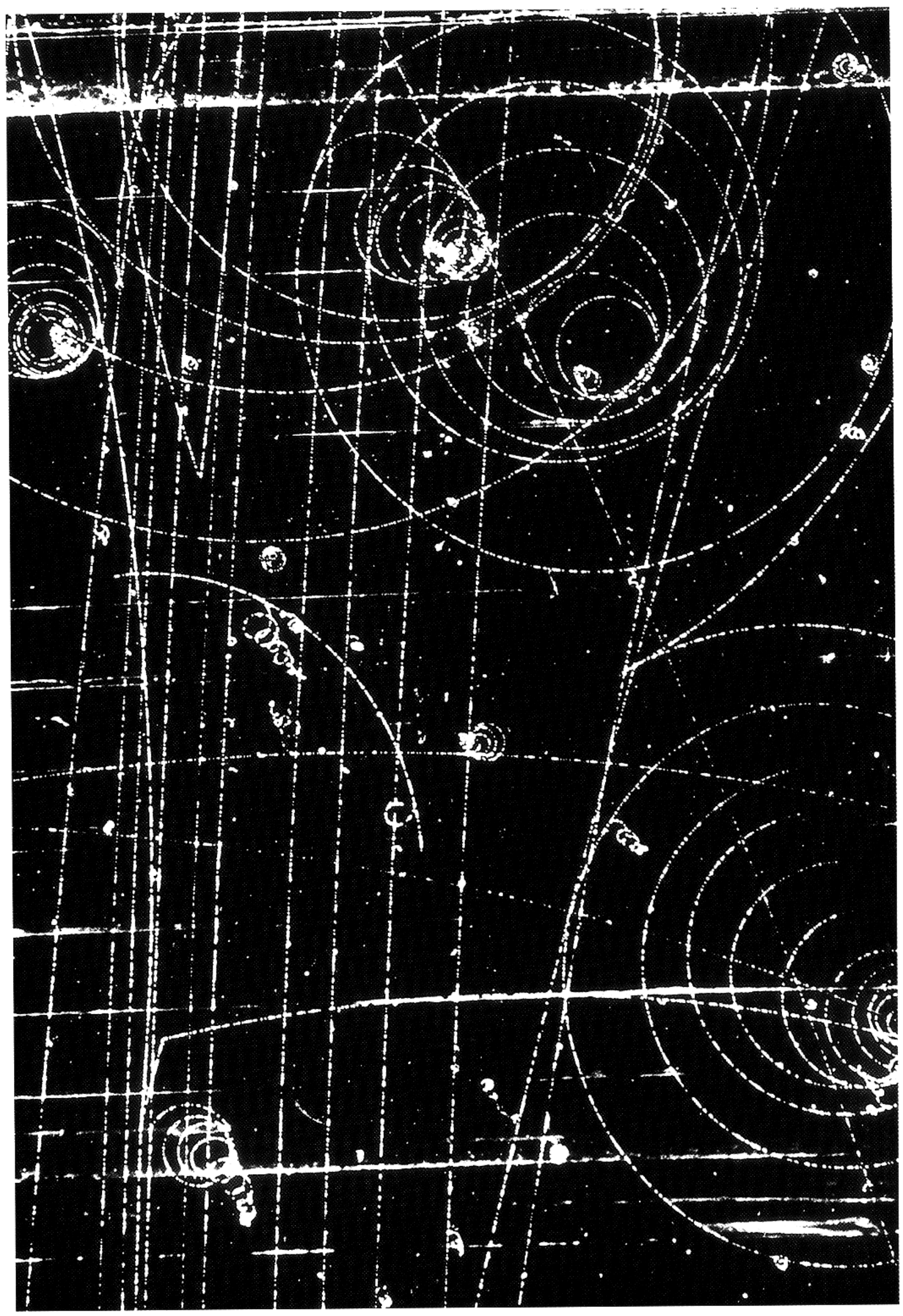


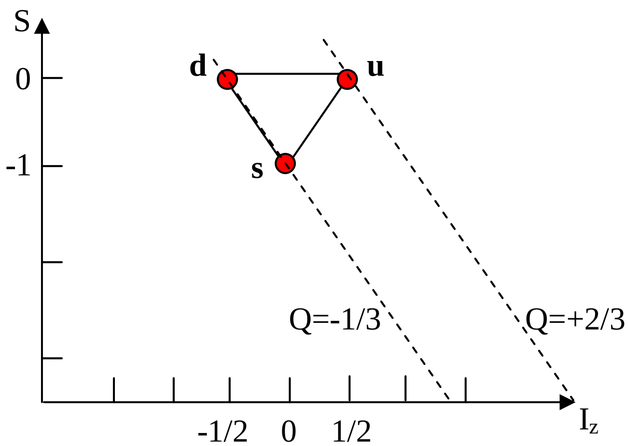
Fig. 7.12 This historic picture from the 200 cm (80 inch) hydrogen bubble chamber at Brookhaven shows the first observation of the omega-minus. A negative kaon (K^-) collides with a proton to produce three particles: an omega-minus (Ω^-), a positive kaon (K^+), and an unseen neutral kaon (K^0), represented by a dotted line in the diagram. The omega-minus travels a short distance (2.5 cm) and then decays, emitting a pi-minus (π^-) that veers sharply to the right, and a neutral xi (Ξ^0) which decays into three more neutral particles – a lambda (Λ) and two gamma ray photons (γ). These neutrals, also marked by dotted lines in the diagram, finally reveal themselves by decaying into visible 'V's: the gamma rays into electron–positron pairs (e^-, e^+), the lambda into a proton (p) and a pi-minus.

Quark Model for hadrons

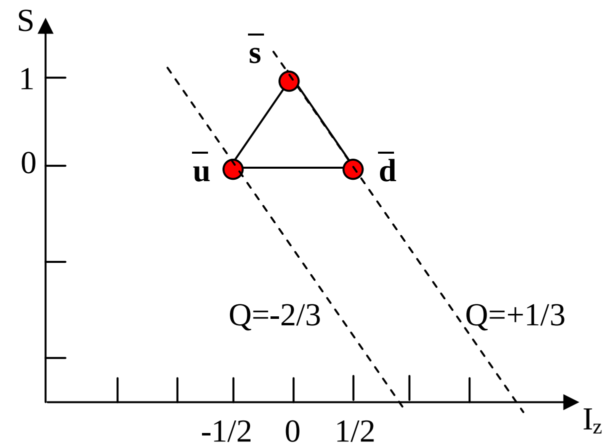
1964 **Gell-Mann** and **Zweig** (independently and after Ω^- discovery) proposed a model of 3 sub-particles that would explain the organization of hadrons in octets, decuplets, and singlets.

Gell-Mann gave them the fanciful name ***quarks*** taken from James Joyce's "Fennegans Wake". It has no real meaning. Gell-Mann took this model very seriously and suggested to look for free quarks. The conventional names for them are **down**-, **up**-, and **strange**-quarks, or ***d***-, ***u***-, and ***s***-quarks, also known as different **flavors**.

The quarks:
1) are *point-like*, described by Dirac's equation (true as of today, i.e. to the best of our knowledge)
2) have *spin-1/2*
3) and *fractional charges* of -1/3*e* for d- and s-quarks and +2/3*e* for u-quark
4) s-quark has strangeness S=-1.



Quark Triplet



Anti-Quark Triplet

Mesons: $\bar{q}q$ $\bar{3} \otimes 3 = 8 \oplus 1$ **(octet and singlet) and can have spin 0, 1, etc.**

Baryons: **qqq** $3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$ **and can have spin ½, 3/2, etc.**

Right away, **the Quark Model**

- explained why there were no mesons with S=±2, or (S=-1, Q=1), or (S=1, Q=-1);
- explained why there were no baryons with S>0, or (S=0, Q=-2)
- accounted fairly well for anomalous magnetic moments of baryons (Sakata model would not)
- explained the mass splits between particles with different S by assuming that s-quark is heavier than u and d
- explained spin-parity relationships (see next page)

However, **the Quark Model** had its own problems

- Psychological: fractional charges! The answer was *so what?*
- Experimental: free quarks have never been seen. The answer was that we did not reach large enough energies to break up hadrons… Or, maybe, the force between quarks is such that they are bound to stay together no matter how hard we hit hadrons…
- Theoretical and fundamental: Decuplet of baryon resonances would violate Pauli principal for fermions. This problem and its solution suggested by O.W. Greenberg in 1964 will be discussed a bit later…

Mesons: $\bar{q}q$

$\bar{3} \otimes 3 = 8 \oplus 1$ (octet and singlet)
can have spins 0, 1, 2, etc.

Nonet of light mesons (quarks have anti-parallel spins and L=0: $J^P=0^-$)[1]

$\bar{d}u$ -- π^+
$\bar{d}s$ -- $\bar{K}^0$
$\bar{u}d$ -- π^-
$\bar{u}s$ -- K^-
$\bar{s}u$ -- K^+
$\bar{s}d$ -- K^0
$\bar{u}u$ -- $\bar{d}d$ -- $\bar{s}s$ mix together to make three orthogonal states π^0, η, η

$\pi^0 = (\bar{u}u - \bar{d}d) / \sqrt{2}$
$\eta' \approx (\bar{u}u + \bar{d}d + \bar{s}s) / \sqrt{3}$ (fully symmetric singlet)
$\eta \approx (\bar{u}u + \bar{d}d - 2\,\bar{s}s) / \sqrt{6}$ (orthogonal to the other two states)

Another set of heavy mesons (quarks have parallel spins and L=0: $J^P=1^-$)

$\bar{d}u$ -- ρ^+
$\bar{d}s$ -- $\bar{K}^{*0}$
$\bar{u}d$ -- ρ^-
$\bar{u}s$ -- K^{*-}
$\bar{s}u$ -- K^{*+}
$\bar{s}d$ -- K^{*0}
$\bar{u}u$ -- $\bar{d}d$ -- $\bar{s}s$ mix together to make three orthogonal states ρ^0, ω, ϕ

$\rho^0 = (\bar{u}u - \bar{d}d) / \sqrt{2}$
$\omega \approx (\bar{u}u + \bar{d}d) / \sqrt{2}$
$\phi \approx (\bar{s}s)$

One can carry on and build states with L=1 and S=0: $J^P=1^+$,
L=1 and S=1: $J^P=2^-$, $J^P=1^-$, $J^P=0^-$
and so on…

All these heavier states are nothing else but excited states (resonances) of the basic 9 mesons. Many of these heavier resonances have been experimentally confirmed. However, as they get heavier and heavier, the number of possible decay modes also increases together with plain phase space; the resonances in general become broader and harder and harder to identify…

[1] Quantum number P, parity of particles, will be discussed later. In Quark Model, parity of a meson $P=(-1)^{L+S+1}$

Baryons: qqq

$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$
can have spin ½, 3/2, 5/2, etc.

Decuplet of baryon resonances (all quarks have parallel spins and L=0: J=3/2)

uuu -- Δ^{++}
uud -- Δ^{+}
udd -- Δ^{0}
ddd -- Δ^{-}

suu -- Σ^{*+}
sud -- Σ^{*0}
sdd -- Σ^{*-}

ssu -- Ξ^{*0}
ssd -- Ξ^{*-}

sss -- Ω^{-}

So far so good…

➔ BUT many baryons in this decuplet have 2 or even 3 identical quarks (fermions) in identical states… This violates the Pauli principle!

Octet of baryons (quarks have two parallel and one anti-parallel spins and L=0: J=1/2)

uuu -- does not exist (corner in the previous decuplet)
uud -- p
udd -- n
ddd -- does not exist (corner in the previous decuplet)

suu -- Σ^{+}
sud -- Σ^{0} and Λ (two states vs. one in the decuplet)
sdd -- Σ^{-}

ssu -- Ξ^{0}
ssd -- Ξ^{-}

sss -- does not exist (corner in the previous decuplet)

➔ WHY do we miss the corner pieces, and why does the central particle exist in two incarnations?

Color

1964 **O. W. Greenberg** suggested a solution that would resolve the baryon problem in the Quark Model. The proposal was to assume that there were three different quarks of each flavor[2], the only difference being in a new quantum number that we now call **color charge**: *red, green, blue*.

The conjecture was that for any observable particle the combined color-charge wave-function must be in color-singlet state, or anti-symmetric with respect to swapping any two quarks.

Note that states such as red-antired or red-blue-green, although appear to have "zero" color are not truly colorless. The analogy with the total spin of two spin-1/2 particles comes very handy here: the two mixed states $(\uparrow\downarrow+\downarrow\uparrow)/\sqrt{2}$ and $(\uparrow\downarrow-\downarrow\uparrow)/\sqrt{2}$ both have zero projection on z-axis, but only the latter one has zero spin, while the former state is a spin-1 states, whose alignment happened to be normal to z-axis.

The requirement of a color-singlet states would automatically take care of non-existence of such exotic states as single quark *q*, di-quark *qq*, quadroquark *qqqq*… These states can never be made colorless.

Solution for the baryon problem:

This simple conjecture explains the structure of the baryon octet and decuplet (L=0 for all quark pairs). Consider the global **Ψ**-function of three quarks. It has three parts for special, spin, and color coordinates:

$$\Psi(1,2,3) = \psi_1(x)\psi_2(x)\psi_3(x) \cdot s_1 s_2 s_3 \cdot \chi_1\chi_2\chi_3$$

where $\psi_1(x)\psi_2(x)\psi_3(x)$ is symmetric (L=0),
while the color part $\chi_1\chi_2\chi_3$ must be anti-symmetric: $\chi_1\chi_2\chi_3 = (rgb - grb + gbr - bgr + brg - rbg) / \sqrt{6}$
and the overall function **Ψ** is required to be anti-symmetric with respect to swapping two identical fermions.

1) Consider three different quarks, all three being of different flavors, ***abc***:
Spin arrangements can be as follows:
$(S_{ab}=1) \times (S_c=1/2) \rightarrow$ $S_{abc} = ½$ and $S_{abc} = 3/2$
$(S_{ab}=0) \times (S_c=1/2) \rightarrow$ $S_{abc} = ½$
➔ This takes care of the central positions in the octet and decuplet: there should be two baryons with spin ½ made of uds quarks (Σ^0 and Λ) and just one baryon with spin-3/2 (Σ^{*0})

2) Consider three quarks of two identical and one different flavors, ***aab***:
To comply with the Pauli principle, the spins of the two identical quarks should be aligned to make spin-function symmetric with respect to swapping two ***a***-quarks (↑↑). This, complemented with anti-symmetric color-function, will make the overall **Ψ** function anti-symmetric:
$(S_{aa}=1) \times (S_c=1/2) \rightarrow$ $S_{aab} = ½$ and $S_{aab} = 3/2$
➔ taking into account, that we have total three different flavors, this would make up six spin-½ and six spin-3/2 baryons (uud, uus, ddu, dds, ssu, ssd) and would fill in the corners of the 6-gons in the octet and decuplet.

3) Consider three quarks of an identical flavor, ***aaa***:
Now spin-function must be symmetric to swaps 1↔2, 1↔3, 1↔3.
The first two should be in spin-1 state.
➔ To get a spin-3/2 state, the third quark should be also aligned with the first two, (↑↑)↑. One can see that this function is also symmetric with respect to swapping 1↔3 and 2↔3, which is needed as well since these pairs are also identical ***a***-type quarks. Therefore spin-3/2 baryons made of three identical quarks are allowed: Δ^{++} (uuu), Δ^- (ddd), Ω^- (sss).
➔ The orthogonal spin-1/2 state is (↑↑)↓ and would be neither symmetric nor asymmetric with respect to swapping 1↔3 and 2↔3. Therefore, these states are not allowed according to the Pauli principle, and uuu, ddd, sss spin-1/2 baryons do not exist.

[2] Of course, this is not a very economical solution and many thought at the time that this motion was basically the last convulsions of the quark model. However, the idea survived, was experimentally verified, and eventually resulted in the Quantum Chromodynamics, quantum field theory of the strong force. Color charges for QCD turned out to be what electric charges for Quantum Electrodynamics. We will discuss all of that later.

Side note on fractional quark charges

1965 **Nambu and Han** suggested another variation of the Quark Model that would not have fractional charges:

u_{red}:	$q = +1e$	d_{red}:	$q = 0$	s_{red}:	$q = 0$
u_{green}:	$q = +1e$	d_{green}:	$q = 0$	s_{green}:	$q = 0$
u_{blue}:	$q = 0$	d_{blue}:	$q = -1e$	s_{blue}:	$q = -1e$
	$\langle q \rangle = +2/3e$		$\langle q \rangle = -1/3e$		$\langle q \rangle = -1/3e$

However, this idea did not withstand experimental tests. E.g., the cross section of deep inelastic scattering of electrons on protons is $\sim\Sigma q^2$ of all constituents of a proton:

→ Gell-Mann–Zweig model gives $(2/3)^2+(2/3)^2+(-1/3)^2 = 5/9$

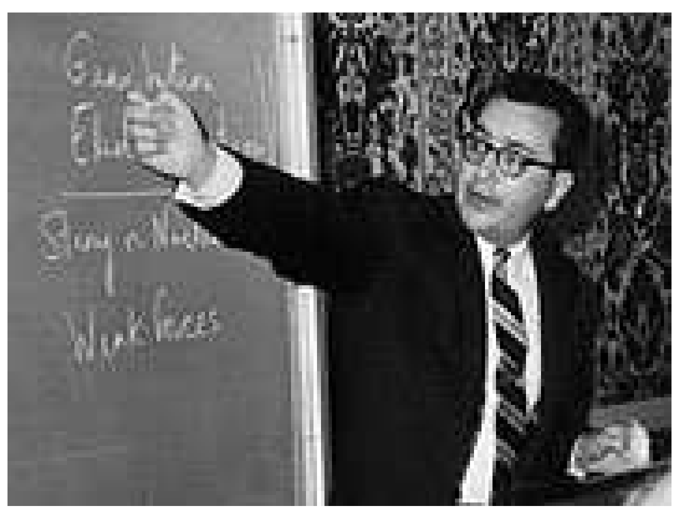
→ Nambu–Han model would give:
$(1^2+1^2+(-1)^2)/6 + (1^2+1^2+(-1)^2)/6 + (1^2+0^2+0^2)/6 + (0^2+1^2+0^2)/6 + (0^2+1^2+0^2)/6 + (1^2+0^2+0^2)/6 = 5/3$,
i.e. a factor of three (!) larger cross section that Gell-Mann-Zweig model would give.

→ The experimental data of late 1960s clearly favored the model with quarks having fractional charges…

Note: The fact that there are three colors and the quark electric charges are multiples of 1/3 does not seem to be accidental[3].

(Almost) final remark

1969 **Gell-Mann** is awarded Nobel Prize for *"for his contributions and discoveries concerning the classification of elementary particles and their interactions"*



[3] This particular charge-color relationship in quark sector as well as matching of lepton-quark generations magically removes nasty triangle anomalies which otherwise would appear in calculations of the perturbative electro-weak loop corrections.

Search for free quarks

- ## Produce free quarks at accelerators:

Just hit hard enough to kick out quarks from hadrons…
Ionization density left behind by a charged particle $\sim q^2/v^2$. A free quark with fractional charge of 1/3*e* would leave a track with ionization density by a factor of $(1/3)^2 = 1/9$ (!) less than a unit-charge particle…
➔ The most recent limit:
Free quark production cross section at the highest available energy (2 TeV) $<10^{-40}$ cm^2
→ compare to solar/reactor neutrino cross section: $\sim10^{-40}$ cm^2
→ compare to Higgs boson production cross section at LHC: $\sim10^{-36}$ cm^2

- ## Current accelerator energy not sufficient? Violent cosmic collision may do the trick:

The early Universe right after Big Bang…
Black holes or whatever that generates cosmic rays with energies up to 10^{20} eV (highest ever detected!)…
Once a free quark is produced, it would be stable…

Look for free quarks in cosmic rays:

Use the same technique as with accelerator searches…
➔ The most recent limit:
Free quark cosmic flux: $<10^{-15}$ cm^{-2} s^{-1}
→ compare to flux of muons on the sea level $\sim10^{-2}$ cm^{-2} s^{-1}
→ compare to cosmic rays with E>10^{20} eV: $\sim10^{-15}$ cm^{-2} s^{-1}

Look for free quarks in various materials:

Meteorites, ancient rocks from ocean bed, dust from upper atmosphere, moon's rock, etc, etc…
Do Millikan-like experiments on levitating small specks of material in electric field with precision $\delta q \sim 1/10e$ or better…

1966 **Gallinaro** conducts the pioneering search of this kind with tiny grains of graphite
→ result negative

…

1977, 1979, 1981 **Fairbank** (Stanford) reports seeing levitating superconducting niobium balls with fractional charge of -0.37±0.03. This would imply density of free quarks of $\sim10^{-20}$ per nucleon.

…

1988 ??? It was pointed out that a subtle magnetic effect could mimic the apparent fractional charge

…

➔ The most recent limit:
Density of free quarks in matter (???) on Earth $<10^{-26}$ per nucleon.

Conclusion: no free quarks have been seen so far…

Baryon magnetic moments

Mesons:

- Light mesons do not have spin and, therefore, cannot have magnetic moments
- Heavy mesons, some of which do have a non-zero spin, do not live long enough for direct measurements.

Baryons:

- All baryons have spins; therefore, they may and do have magnetic moments
- Proton and weakly decaying baryons (n, Σ^-, Σ^+, Λ, Ξ^-, Ξ^0, Ω-), 8 baryons overall, live long enough for direct measurement of their magnetic moments by observing their precession in a uniform magnetic field or via beam splitting in a non-uniform magnetic filed. Σ^0 decays electromagnetically ($\Sigma^0 \rightarrow \Lambda\gamma$) and lives ~$10^{-20}$ s, too short time for direct measurements.
- Other baryon resonances do not live long enough for direct observation of their magnetic moments.

Quarks:

Quarks are Dirac particles and their magnetic moments must be μ=q/2m

Take masses of up- and down-quarks approximately equal to each other[4] (m_0) while s-quark should be heavier (m_s). Then,

$\mu_u = (2/3) \cdot (e/2m_0)$

$\mu_d = (-1/3) \cdot (e/2m_0)$

$\mu_d = (-1/3) \cdot (e/2m_s)$

Extract m_0 and m_s from data (perform consistency check with expectations):

Proton (uud) has J=1/2 and is made of uu-pair with S_{uu}=1 and d-quark with S=1/2.

Consider it with its spin aligned upward. Then, using Clebsch-Gordon coefficient tables

$$\left(J=\frac{1}{2};J_z=\frac{1}{2}\right)=\sqrt{\frac{2}{3}}(1;1)\left(\frac{1}{2};-\frac{1}{2}\right)-\sqrt{\frac{1}{3}}(1;0)\left(\frac{1}{2};\frac{1}{2}\right)$$

This will result in effective magnetic moment:

$$\mu_p=\frac{2}{3}(2\mu_u-\mu_d)+\frac{1}{3}\mu_d=\frac{4}{3}\mu_u-\frac{1}{3}\mu_d=\frac{e}{2m_0}$$

Experimental value: $\mu_p = 2.79\ \mu_N = 2.79\ (e/2m_N)$

From this, we can derive: $m_p = m_N /2.79 \sim 336$ MeV

As expected (!), if we take the mass of up and down quarks to be about 1/3 of a mass of nucleon…

Λ (uds), where ud-pair has total spin=0[5] and, therefore, this pair cannot have magnetic moment. Consequently, $\mu_\Lambda = \mu_s = (-1/3) \cdot (e/2m_s)$.

Experimental value: $\mu_\Lambda = -1.61\ \mu_N$

This allows to extract m_s=510 MeV, i.e. ~170 MeV heavier than u- and d-quarks…

As expected (!) from the mass splits in baryon decuplet/octet (~150-190 MeV)…

[4] This follows from the observed isospin invariance…

[5] (uds)-state with (ud)-pair having total spin 1 is Σ^0, a part of Σ-triplet: Σ^+(uus) must have uu-pair's spin equal 1; similarly, Σ^-(dds) must have dd-pair's spin equal 1. See previous lecture.

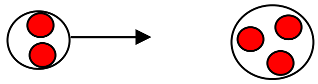
Now we are ready to predict magnetic moments for all the remaining baryons:

Baryon	Quark Model Formula	Prediction	Experiment	Deviation
P	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_d$		2.793	
Λ	μ_s		-0.613±0.004	
N	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_u$	-1.86	-1.913	0.05, or 3%
Σ^+	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_s$	2.69	2.46±0.01	0.23, or 9%
Σ^0	homework		n/a	-
Σ^-	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_s$	-1.04	-1.16±0.03	0.12, or 12%
Ξ^0	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_u$	-1.44	-1.25±0.014	0.19, or 9%
Ξ^-	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_d$	-0.51	-0.65±0.003	0.14, or 28%
Ω^-	$3\mu_s$	-1.84	-2.02±0.05	0.18, or 8%

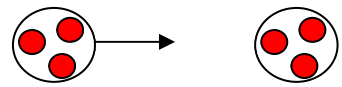
The agreement, typically <0.2 over the range of ~4 from -2 to 2.5, is not that bad at all for the very simple model that we used (basically, we treated the quarks as heavy, non-relativistic, "non-interacting" particles put in one bag; all we accounted for is the Pauli principle and required the overall color-singlet state).

Early verifications of the Quark Model

π+N and p+N cross-sections:

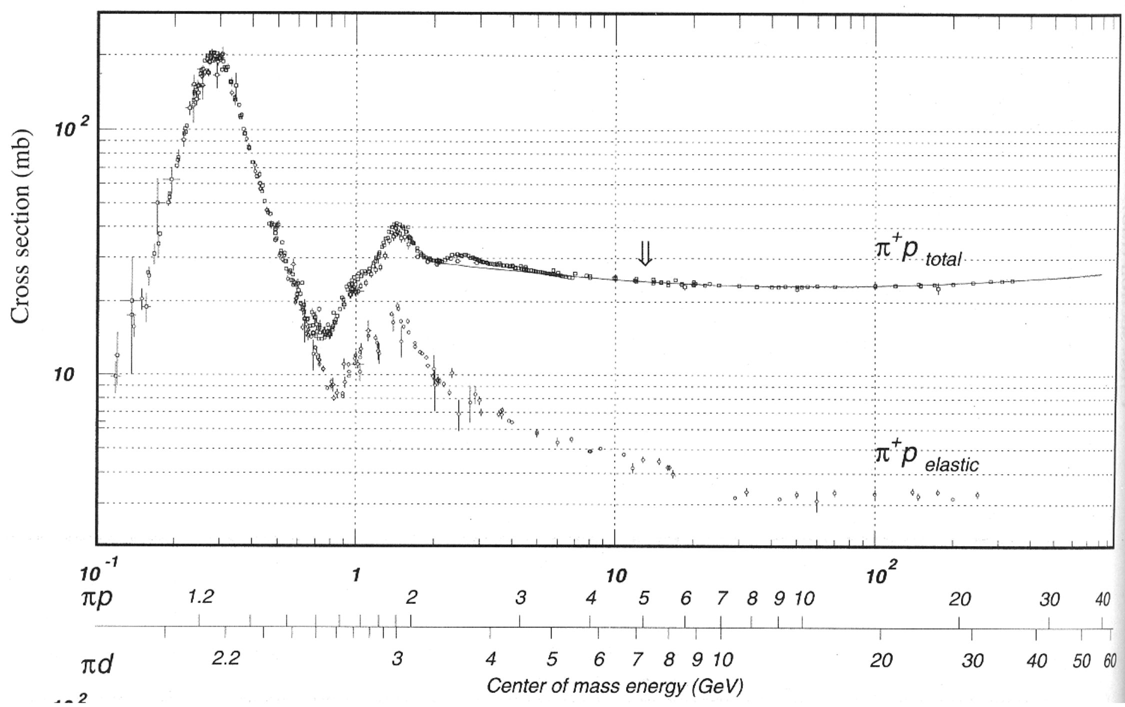


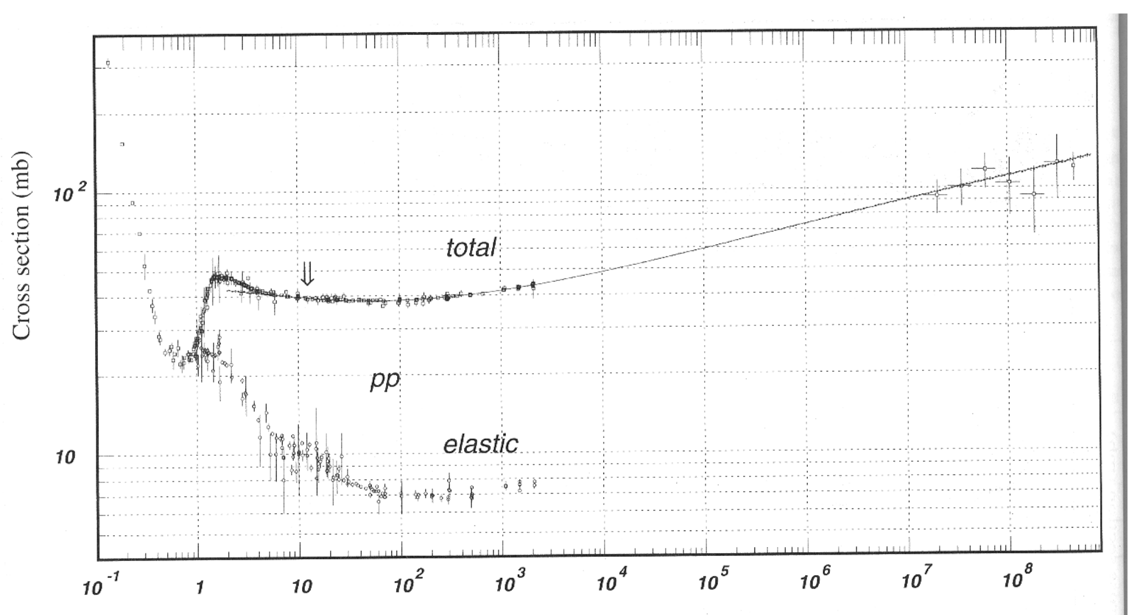
$\sigma(\pi N) \sim 2\times3$



$\sigma(pN) \sim 3\times3$

➔ Predict: $\sigma(\pi N) / \sigma(pN) = 2/3$
➔ Experimental value: 25 mb / 40 mb = 0.63





Ratio of cross-sections ($e^+ e^- \rightarrow$ *hadrons*) / ($e^+ e^- \rightarrow \mu^+ \mu^-$)

$$\sigma \sim \Sigma\, e^2\, q_i^2$$

Muon pair production cross section is

$\sigma_0 = \sigma(e^+ e^- \rightarrow \mu^+ \mu^-) = \text{Const}\cdot e^4$

When energy is small and only three light quarks (u, d, s) are accessible, the hadron production cross section is

$\sigma_h = \sigma(e^+ e^- \rightarrow \textit{hadrons}) = \text{Const}\cdot e^2\cdot(N_c\cdot(2/3e)^2 + N_c\cdot(-1/3e)^2 + N_c\cdot(-1/3e)^2)$.

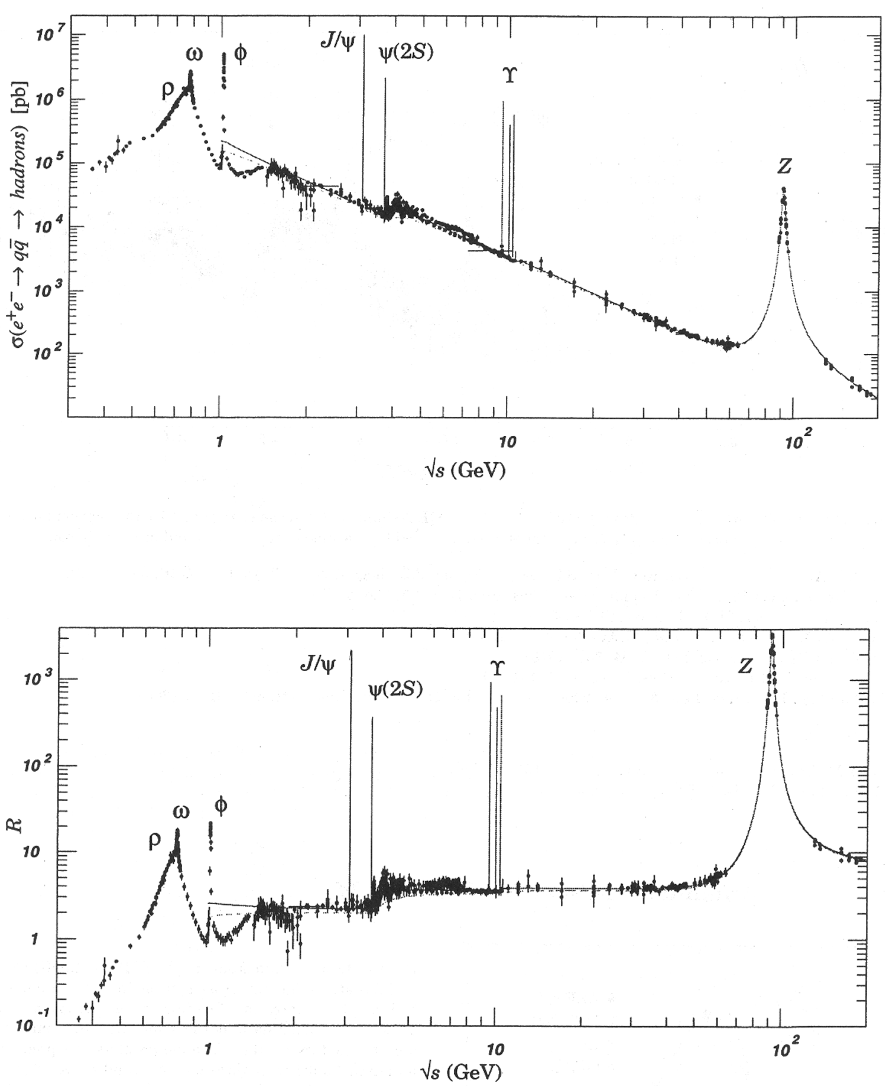
Note that factors of N_c=3 are there to account for three different colors.

➔ Predict: the ratio R(uds) = σ_h/σ_0 = 2. Note this ratio is very sensitive to the number of colors!

➔ Experiment: the ratio away from resonances between 1.5-3 GeV is close to 2…

As the energy of collision rises, one should and does see two more steps as the heavier quarks become available: R(udsc) = 10/3 and R(udscb)=4. These data became available in the second half of 1970s…

σ and R in e^+e^- Collisions

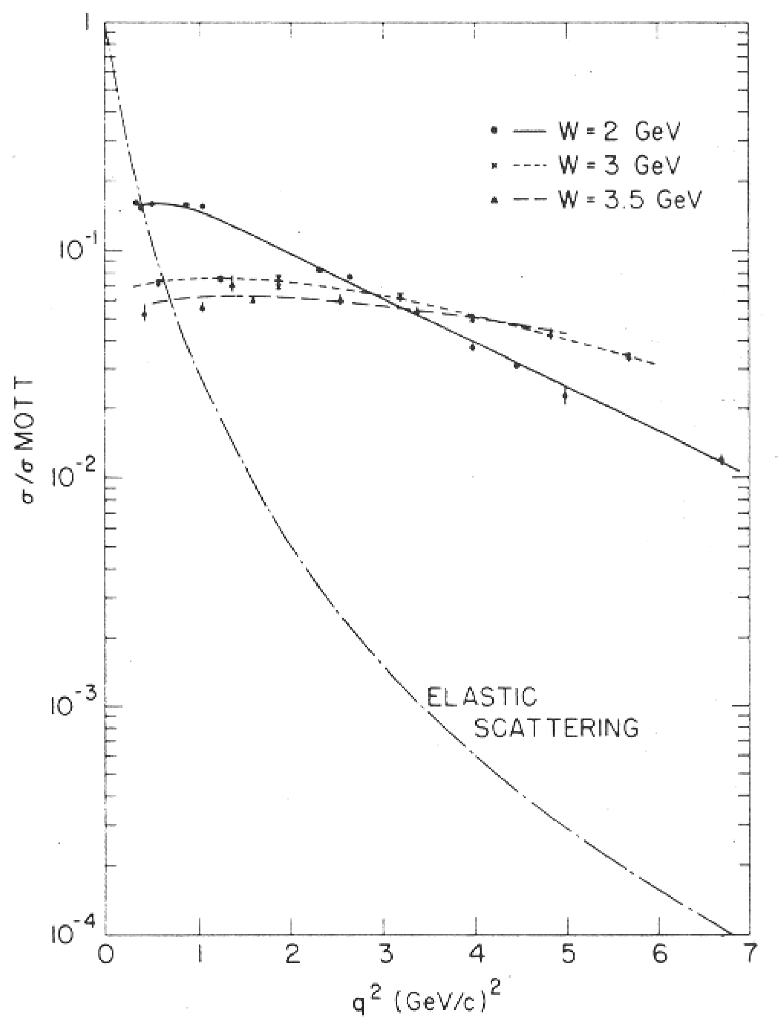


Deep inelastic scattering $e^- + N \rightarrow e^- + anything$

Remember that in 1956 bombardment of protons with electrons of ~200 MeV revealed deviations from the Rutherford formula (properly modified to account for spins and proton's anomalous magnetic moment)—the proton would appear to have a fuzzy charge distribution spread over the region of ~1 fm. As the result not too many electrons could be scattered at large angles…

1967-73 A series of experiments carried out by **Friedman, Kendall, Taylor,** and there coworkers at Stanford convincingly revealed the presence of point-like objects inside nucleons. As the energy of electrons bombarding nucleons was 100-fold increased to about 20 GeV, they would now scatter more and more at larger angles and would be accompanied by debris of hadrons resulted from nucleons being broken up (no free quarks would show, however).

A very broad range of results could be explained by assuming that protons and neutrons consisted from essentially free point-like quarks…



1990 **Friedman, Kendall, Taylor** are awarded the Nobel Prize for *"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"*

"Seeing" quarks as jets…

Early indications for a presence of jet like particl flow in hard collisions:

???? $\nu + N \to \mu + anything$, $\mu + N \to \mu + anything$ (bubble chambers). Single jets. Any images???

1972 $p + p \to anything$, ISR turns on at CERN. Dijets. Any images???

First very conclusive (quantitative) evidence

1975 **Gail Hanson** and coworkers report the first firm statistically-supported evidence for quark dijets in $e^+ e^- \to$ *hadrons* events (SPEAR at Stanford). Polar angular distribution of dijets implies that quarks must have spin-½. (Figures below are from later publications.)