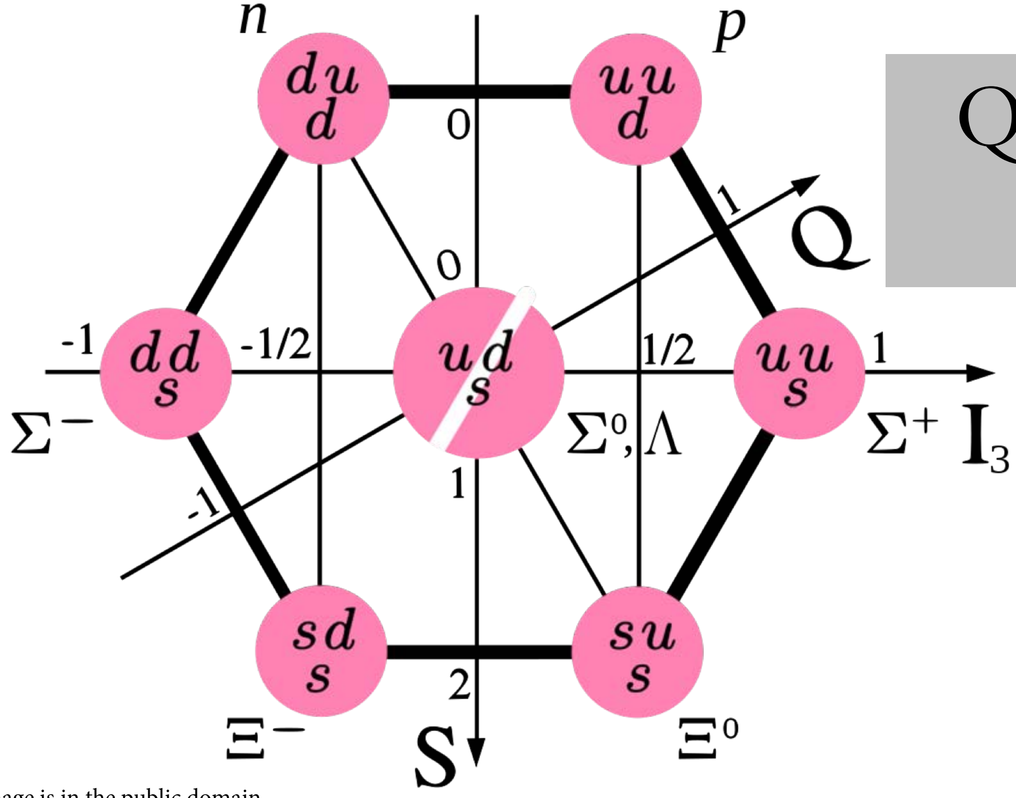

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Quarks, QCD, and the Rise of the Standard Model

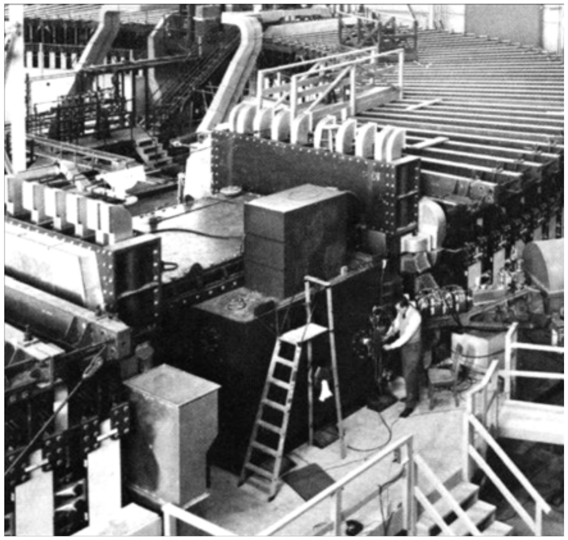
8.225 / STS.042, Physics in the 20th Century
Professor David Kaiser, 30 November 2020

1. Particle Zoo: Classification

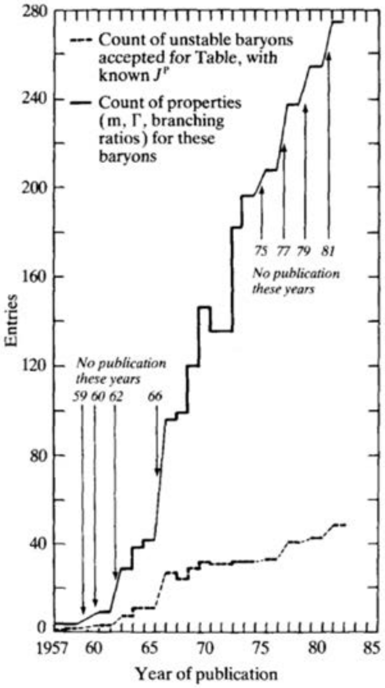
2. Quarks: Fact or Fiction?

3. QCD: Field Theory Returns

The Particle Zoo



Berkeley Bevatron, 1955



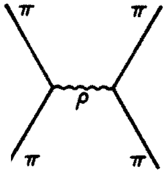
Beginning soon after the Second World War, enormous particle accelerators yielded evidence of *huge numbers* of nuclear particles.

First challenge: most of the particles interacted *strongly* with each other ($g^2 \sim 15$ rather than $e^2 \sim 1/137$), so perturbative methods broke down.

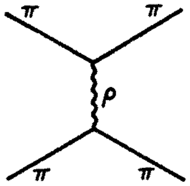
Second challenge: could all 100+ particles really be equally "elementary" or fundamental?

Geoffrey Chew's program of "nuclear democracy" and the "bootstrap": maybe all of these particles were *bound states of each other*. Aim to *replace* QFT while focusing on *dynamics*: the self-consistent forces among all the nuclear particles.

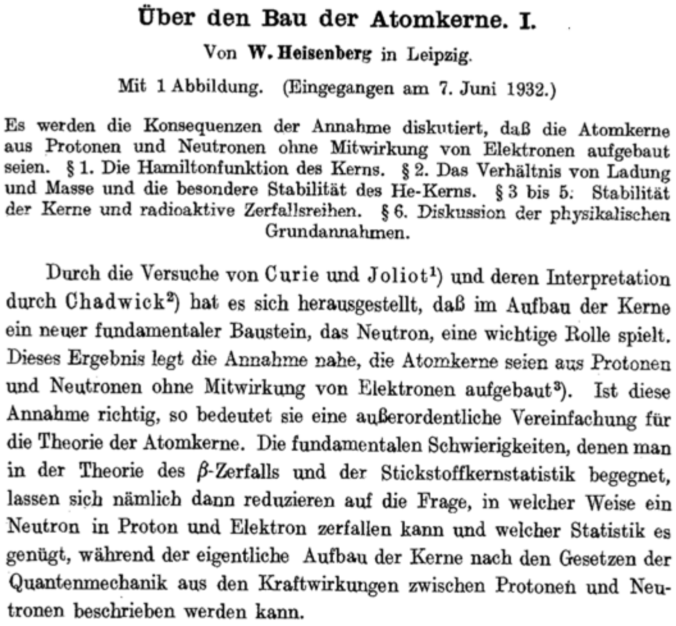
Step 1: A ρ produces an ***attractive force*** between two pions, causing them to approach each other: $F_{\text{force}}(m_\rho, g)$.



Step 2: Upon colliding, the two pions produce a new ***composite*** particle, the ρ: $F_{\text{res}}(m_\rho, g)$.



The Particle Zoo: Classification



Über den Bau der Atomkerne. I.

Von **W. Heisenberg** in Leipzig.

Mit 1 Abbildung. (Eingegangen am 7. Juni 1932.)

Es werden die Konsequenzen der Annahme diskutiert, daß die Atomkerne aus Protonen und Neutronen ohne Mitwirkung von Elektronen aufgebaut seien. § 1. Die Hamiltonfunktion des Kerns. § 2. Das Verhältnis von Ladung und Masse und die besondere Stabilität des He-Kerns. § 3 bis 5. Stabilität der Kerne und radioaktive Zerfallsreihen. § 6. Diskussion der physikalischen Grundannahmen.

Durch die Versuche von Curie und Joliot1) und deren Interpretation durch Chadwick2) hat es sich herausgestellt, daß im Aufbau der Kerne ein neuer fundamentaler Baustein, das Neutron, eine wichtige Rolle spielt. Dieses Ergebnis legt die Annahme nahe, die Atomkerne seien aus Protonen und Neutronen ohne Mitwirkung von Elektronen aufgebaut3). Ist diese Annahme richtig, so bedeutet sie eine außerordentliche Vereinfachung für die Theorie der Atomkerne. Die fundamentalen Schwierigkeiten, denen man in der Theorie des β-Zerfalls und der Stickstoffkernstatistik begegnet, lassen sich nämlich dann reduzieren auf die Frage, in welcher Weise ein Neutron in Proton und Elektron zerfallen kann und welcher Statistik es genügt, während der eigentliche Aufbau der Kerne nach den Gesetzen der Quantenmechanik aus den Kraftwirkungen zwischen Protonen und Neutronen beschrieben werden kann.

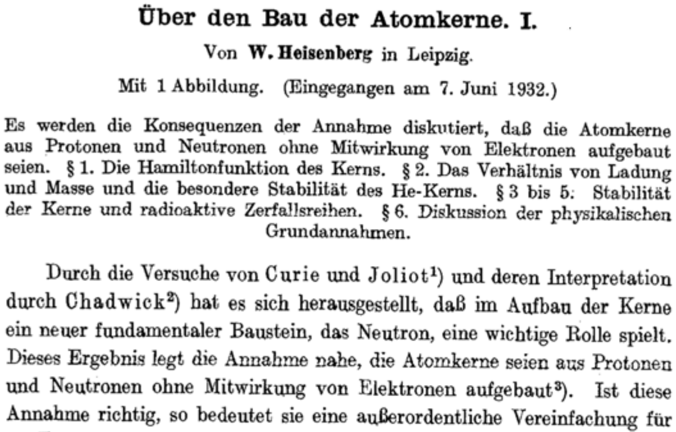
Werner Heisenberg, "On the structure of atomic nuclei," 1932

During the 1950s and 1960s, some particle theorists pursued a *distinct approach* to the challenge of the particle zoo: *classification*. They set aside the question of dynamics to focus on ways to *group* various particles into "families," focusing on "internal symmetries."

This approach hearkened back to the idea of *isospin*, first introduced by *Werner Heisenberg* in 1932, just a few months after *James Chadwick* presented evidence of the *neutron*.

Early experiments had suggested that in nuclear interactions, neutrons and protons had the *same interaction strength*, whether one considered p-p, p-n, or n-n scattering. *Heisenberg*: maybe they're the *same particle* in one of two *internal states*. The symmetry was broken due to electromagnetic effects—just as the electron state "spin up" is only distinguished from "spin down" in an external magnetic field.

The Particle Zoo: Classification



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“**nucleon**”: one type of particle that could occur in one of two *internal states* of “isospin”

$$p^{+}: \quad I = +\frac{1}{2}$$

$$n^{0}: \quad I = -\frac{1}{2}$$

During the 1950s and 1960s, some particle theorists pursued a *distinct approach* to the challenge of the particle zoo: *classification*. They set aside the question of dynamics to focus on ways to *group* various particles into “families,” focusing on “internal symmetries.”

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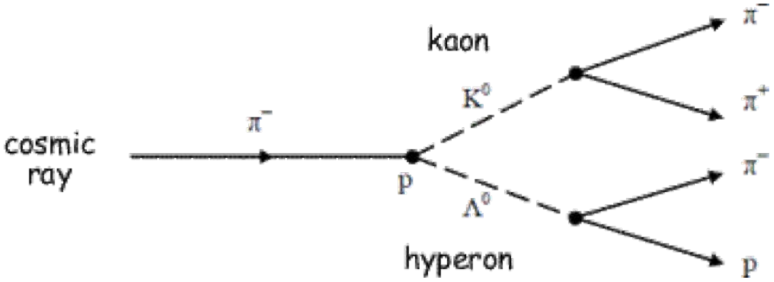
“Associated Production”

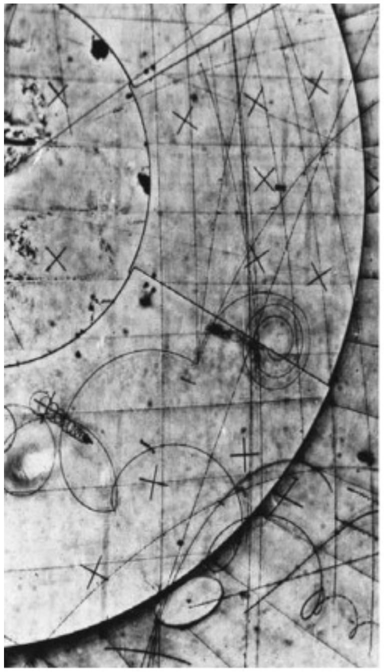


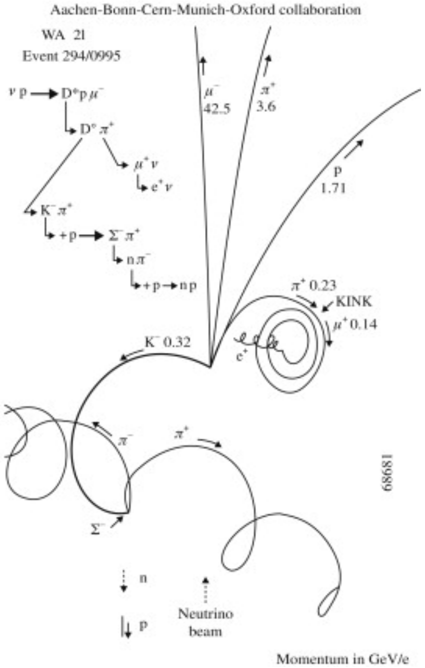
After the war, physicists noticed that some of the new particles—dubbed “strange,” because they were unexpected and unfamiliar—always seemed to be produced *together* during particle collisions, such as the K and Λ particles or K and Σ particles:

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

$$p^+ + \pi^- \longrightarrow \Sigma^- + K^+$$

Murray Gell-Mann and *Abraham Pais* suggested that a new quantum number, “*strangeness*” charge, existed and must be conserved: $S(p, n, \pi) = 0,\ S(K, \Lambda, \Sigma) = \pm 1$.





Hypercharge

In 1960, *Gell-Mann* and (separately) *Yuval Ne'eman* found that a certain combination of these new "charges" could account for even larger patterns.

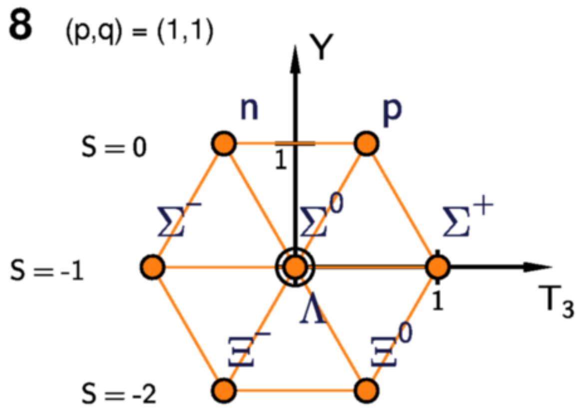
"*Hypercharge*": $Y = \underset{\text{baryon}}{\underset{\uparrow}{B}} + \underset{\text{strangeness}}{\underset{\uparrow}{S}}$

Electric charge: $Q = \underset{\text{isospin}}{\underset{\uparrow}{I}} + \underset{\text{hypercharge}}{\underset{\uparrow}{Y}}/2$

proton: $I = +\frac{1}{2}$, $Y = (1 + 0)$, so $Q = (\frac{1}{2} + \frac{1}{2}) = +1$

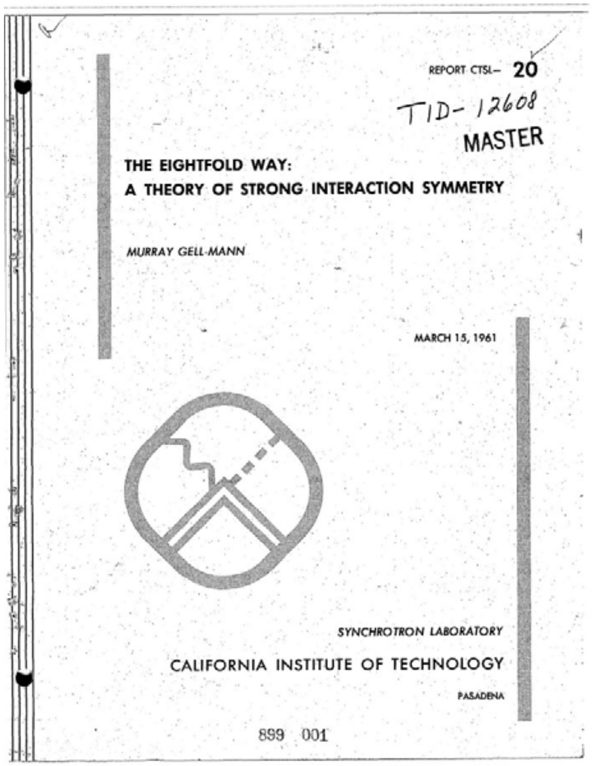
neutron: $I = -\frac{1}{2}$, $Y = (1 + 0)$, so $Q = (-\frac{1}{2} + \frac{1}{2}) = 0$

"*Eightfold Way*"*: Gell-Mann found that he could arrange *groups* of particles by *hypercharge* and *isospin*



* Gell-Mann borrowed the term for the Buddhist's 8-step path to achieving nirvana.

Hypercharge



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MASTER

THE EIGHTFOLD WAY:
A THEORY OF STRONG INTERACTION SYMMETRY

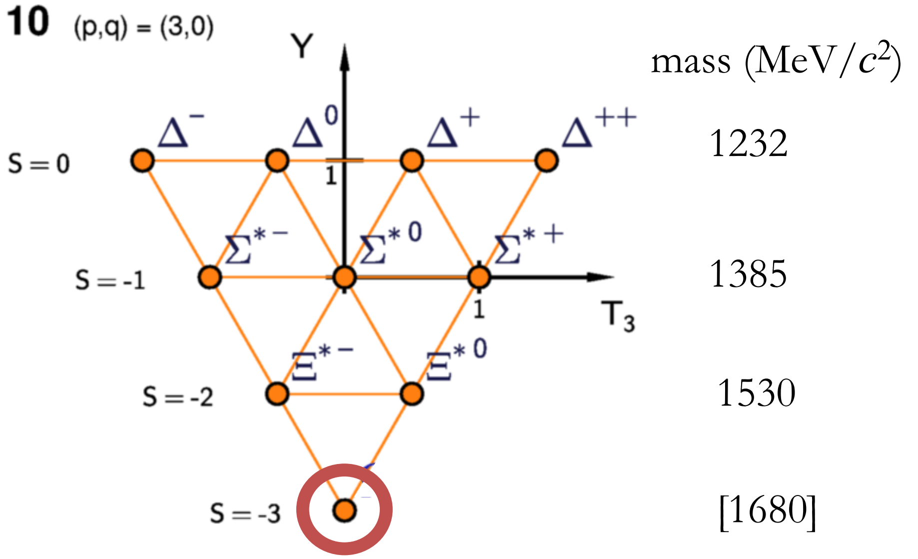
MURRAY GELL-MANN

MARCH 15, 1961

SYNCHROTRON LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA

899 001

Gell-Mann grouped other particles by hypercharge and isospin, and found a 10-particle pattern *with a gap*. Not only did it seem likely that a single particle with $Y = -2$, $I = 0$ should exist, he also noted a pattern among the particles' *masses*.

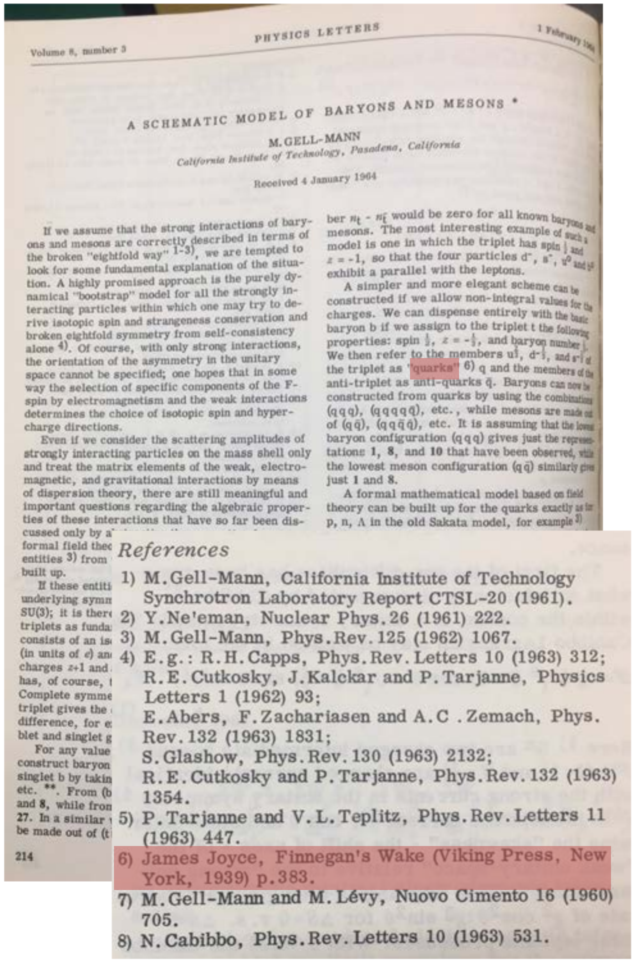


At a conference in 1962, *Gell-Mann* predicted that such a particle would be found with these specific properties. In 1964, experimentalists announced its discovery: the Ω^- particle, with mass 1672 MeV/c^2.

Questions?

Quarks: Fact or Fiction?

Within 13 days of each other in January 1964, *Gell-Mann* and (separately) *George Zweig* proposed that the symmetries among nuclear particles could be associated with *three constituent particles* (“quarks” or “aces”).



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A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means of dispersion theory, there are still meaningful and important questions regarding the algebraic properties of these interactions that have so far been discussed only by a
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ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and

exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q q q)$, $(q q q q \bar{q})$, etc., while mesons are made out of $(q \bar{q})$, $(q q \bar{q} \bar{q})$, etc. It is assuming that the lowest baryon configuration $(q q q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q \bar{q})$ similarly gives just **1** and **8**.

A formal mathematical model based on field theory can be built up for the quarks exactly as for p, n, Λ in the old Sakata model, for example 3)

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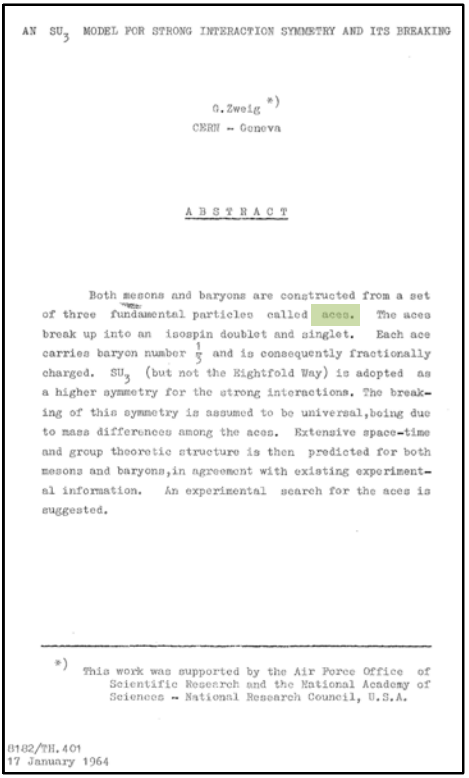
8) N.Cabibbo, Phys. Rev. Letters 10 (1963) 531.



AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G.Zweig *)
CERN – Geneva

A B S T R A C T

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time and group theoretic structure is then predicted for both mesons and baryons, in agreement with existing experimental information. An experimental search for the aces is suggested.

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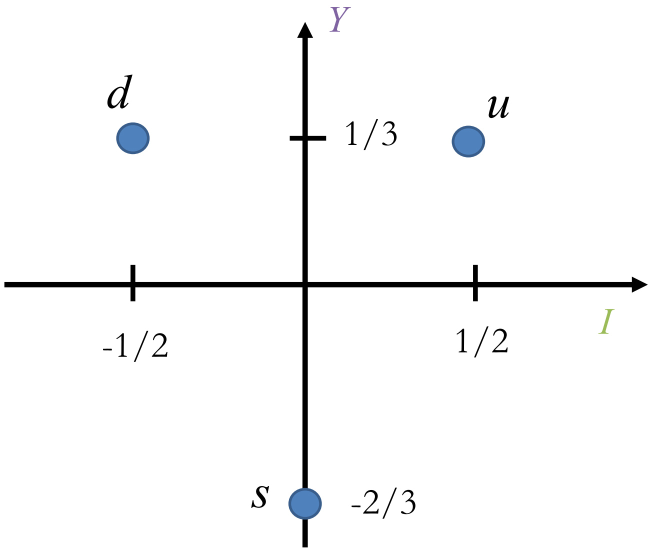
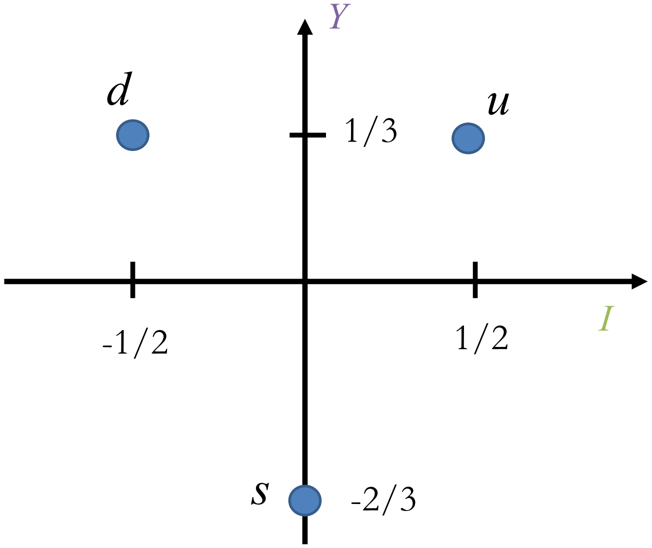
*) This work was supported by the Air Force Office of Scientific Research and the National Academy of Sciences – National Research Council, U.S.A.

8182/TH.401
17 January 1964



Quarks: Fact or Fiction?



	B	S	Y	I	Q
u	1/3	0	1/3	1/2	+2/3
d	1/3	0	1/3	-1/2	-1/3
s	1/3	-1	-2/3	0	-1/3

“*Hypercharge*”: $Y = B + S$

Electric charge: $Q = I + Y/2$

With these assignments, *Gell-Mann* and *Zweig* could account for *all* the octet and decuplet patterns among nuclear particles: each baryon could be accounted for as a set of 3 constituent quarks, while mesons were quark-antiquark pairs.

$p^+ = u\,u\,d$

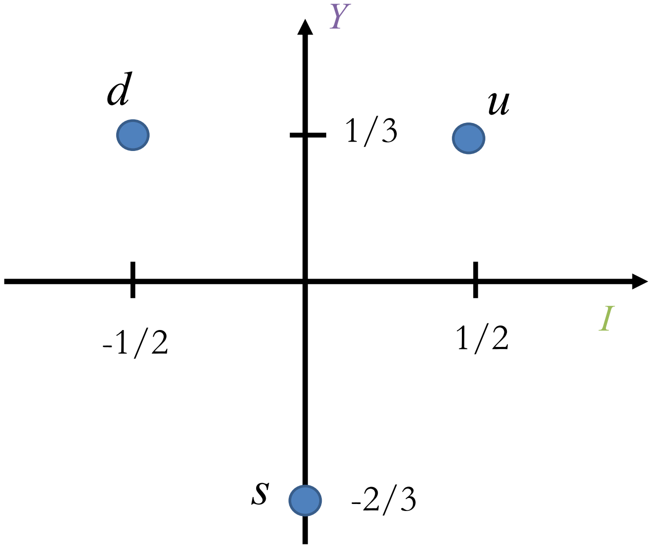
$n^0 = u\,d\,d$

$\Omega^- = s\,s\,s$

$\pi^+ = u\,\overline{d}$

$\pi^- = \overline{u}\,d$

Quarks: Fact or Fiction?



	B	S	Y	I	Q
u	1/3	0	1/3	1/2	+2/3
d	1/3	0	1/3	-1/2	-1/3
s	1/3	-1	-2/3	0	-1/3

"*Hypercharge*": $Y = B + S$

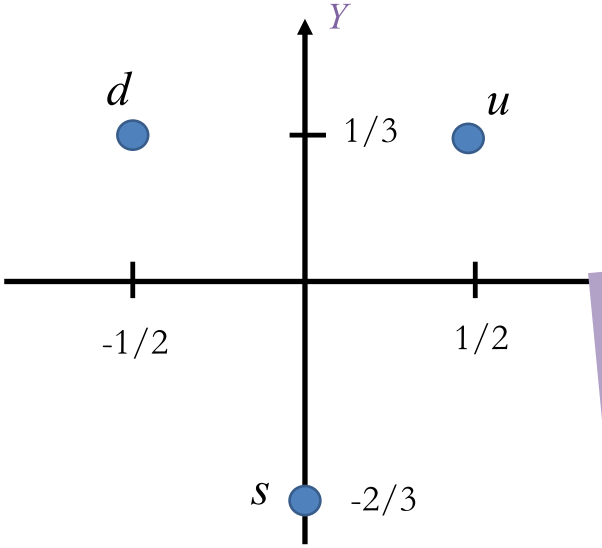
Electric charge: $Q = I + Y/2$

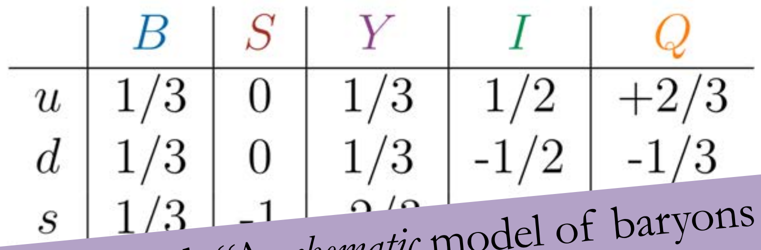
But these assignments raised new questions:

1. *fractional* electric charges?
2. Pauli exclusion principle forbids bound states of 3 identical spin-1/2 particles ($\Omega^- = sss$?)
3. *dynamics*: how do these objects interact with each other?

$$p^+ = u\,u\,d$$
$$n^0 = u\,d\,d$$
$$\Omega^- = s\,s\,s$$
$$\pi^+ = u\,\overline{d}$$
$$\pi^- = \overline{u}\,d$$

Quarks: Fact or Fiction?





	B	S	Y	I	Q
u	1/3	0	1/3	1/2	+2/3
d	1/3	0	1/3	-1/2	-1/3
s	1/3	-1	[illegible]	[illegible]	[illegible]

Gell-Mann hedged: “A *schematic* model of baryons and mesons”: “It is fun to speculate about the way quarks would behave *if they were physical particles* of finite mass (instead of *purely mathematical entities*). ... A search for stable quarks at the highest energy accelerators would help to *reassure us of the non-existence of real quarks*.”

George Zweig’s preprints were never accepted for publication!

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$$n^0 = u\,d\,d$$
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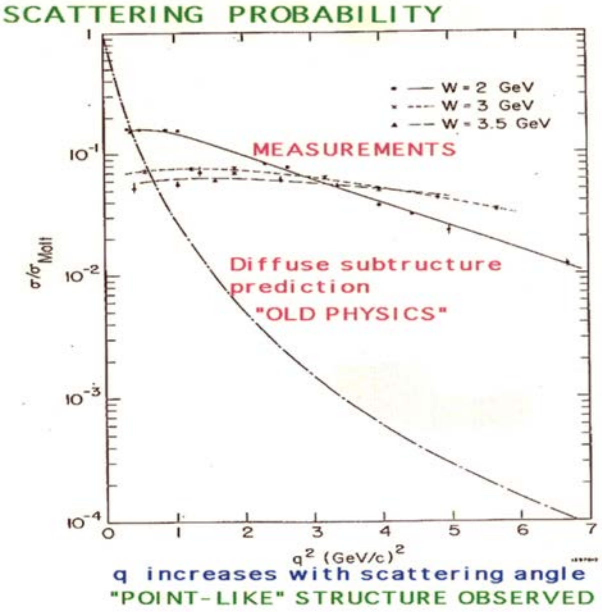
$$\pi^- = \overline{u}\,d$$

SLAC-MIT Experiments

SLAC Magnetic Spectrometers

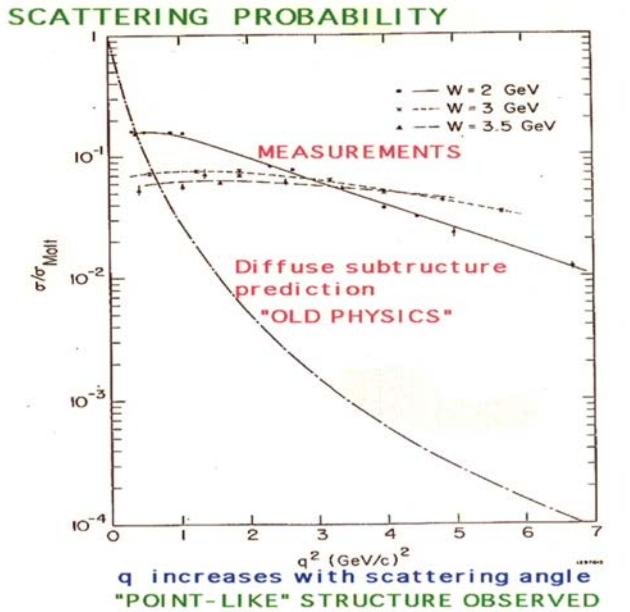
The *Stanford Linear Accelerator Laboratory* (SLAC) began operation in 1966. One of the first sets of experiments was directed by MIT's *Jerry Friedman* and *Henry Kendall*: scatter high-energy electrons off of protons.

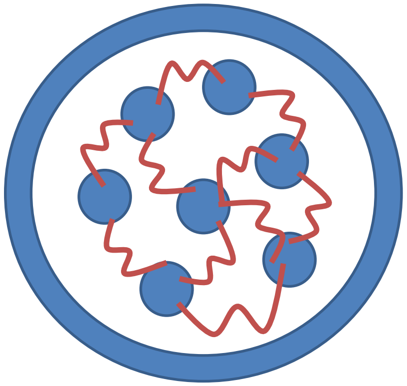
This was essentially a re-play of *Rutherford scattering*. The results for scattering rates versus angle were consistent with *internal structure* within each proton: tiny scattering sites.



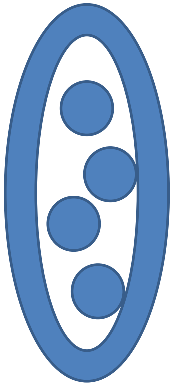
“Partons”

Richard Feynman and *James Bjorken* interpreted the SLAC-MIT scattering data in terms of “partons” (*not* necessarily quarks).





A proton at low energy would be a *big mess*: strong internal forces, a jumble of moving parts.



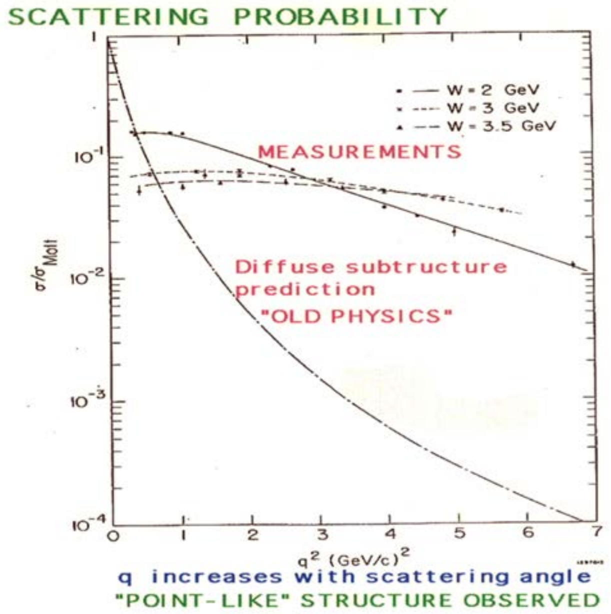
As seen by the speeding electron, the proton would undergo *length contraction* and its internal dynamics would be slowed by *time dilation*. Partons would effectively behave like *free* (non-interacting) stationary targets.

A victory for quarks? Not right away

Gell-Mann’s quarks:
Low-energy *constituents*, strongly interacting (bound)

Feynman’s partons:
High-energy *scatterers*, effectively *free* (non-interacting)

“Partons”



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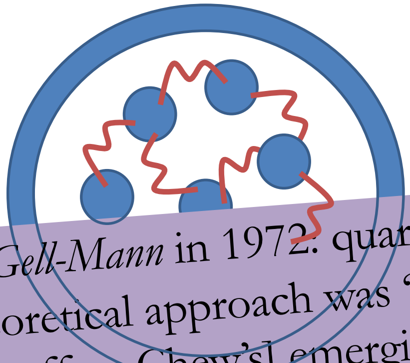

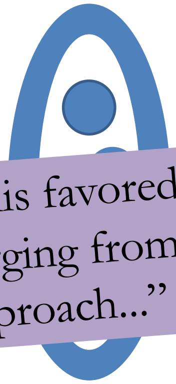

Gell-Mann in 1972: quarks are “fictitious” and his favored theoretical approach was “equivalent to that emerging from [Geoffrey Chew’s] emerging bootstrap-duality approach…”

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A victory for quarks? Not right away

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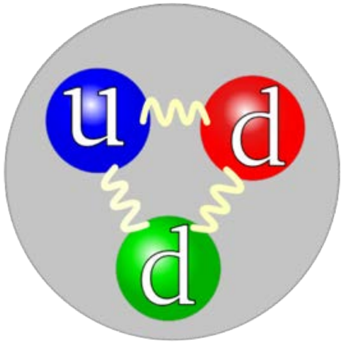
Questions?

QCD: Field Theory Returns

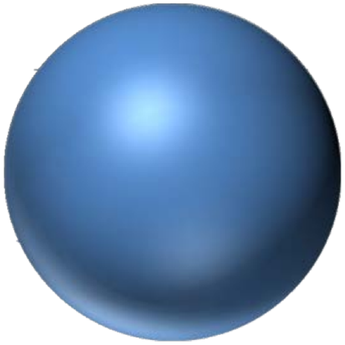


Between 1972-74, *Murray Gell-Mann*, *Harald Fritzsch*, and colleagues developed a new *dynamical* theory of the strong nuclear force. Cast in analogy to quantum electrodynamics (QED), the new model focused on *quarks* (analogous to electrons) interacting by exchanging force-carrying *gluons* (analogous to photons).

New idea: "color" charge. Each quark carries (yet another) internal quantum number (**red**, **green**, or **blue**), so they called their new model "**quantum *chromo*dynamics**" (QCD). A few assumptions: color charge is *conserved*; free particles must have an exact *balance* among the color charges; and the interactions among quarks are *symmetric* with respect to permutations of the color charge.

This helped resolve puzzles like the Ω^-. Such a particle *could* be a bound state of 3 *s* quarks without violating the Pauli exclusion principle: $\Omega^- = s\ s\ s$.

Gauge Symmetries



Central to QCD is the idea of *symmetry*: some property of the system remains *unchanged* (or "invariant") even following *transformations*.

As an analogy, consider a *sphere*: its appearance remains invariant even if it is *rotated* by an arbitrary angle along any axis. Other objects obey *discrete* symmetries, e.g. rotating a *square* by $\theta = n\pi/2$.

Likewise, if we represent a quark by a quantum field $\psi(\mathbf{x},t)$, we may perform *rotations* in (abstract) "color-space": $\psi(\mathbf{x},t) \to \psi'(\mathbf{x},t) = \psi(\mathbf{x},t)e^{i\theta(\mathbf{x},t)}$. (These are "local" transformations: the rotation angle itself can depend on $\mathbf{x}$ and t.) But any *observable* features of the system can only depend on $|\psi|^2 = |\psi'|^2$.

What about *dynamics*? The kinetic energy of such a field depends on $\left(\frac{\partial}{\partial t}\psi(\mathbf{x},t)\right)\left(\frac{\partial}{\partial t}\psi^*(\mathbf{x},t)\right)$.

Under a local transformation, the kinetic energy does *not* remain invariant:

$$\begin{aligned}\frac{\partial}{\partial t}\psi(\mathbf{x},t) &\to \frac{\partial}{\partial t}\psi'(\mathbf{x},t)\\ &= \frac{\partial}{\partial t}\left[\psi(\mathbf{x},t)e^{i\theta(\mathbf{x},t)}\right] \neq e^{i\theta(\mathbf{x},t)}\frac{\partial}{\partial t}\psi(\mathbf{x},t)\end{aligned}$$

Gauge Fields

To maintain symmetry under local transformations, *Gell-Mann* and *Fritzsch* added in *gluons*: "**gauge fields**" A_μ whose sole purpose is to enforce the relevant symmetry.

One may then construct a "**covariant derivative**," $\mathcal{D}_\mu \equiv \partial_\mu + igA_\mu$. Under local transformations, require

$$\psi(\mathbf{x},t) \to \psi'(\mathbf{x},t) = \psi(\mathbf{x},t)e^{i\theta(\mathbf{x},t)} \quad \textit{and} \quad A_\mu(\mathbf{x},t) \to A'_\mu(\mathbf{x},t) = A_\mu(\mathbf{x},t) + \frac{1}{g}\partial_\mu\theta(\mathbf{x},t).$$

Then $\mathcal{D}_\mu\psi(\mathbf{x},t) \longrightarrow e^{i\theta(\mathbf{x},t)}\mathcal{D}_\mu\psi(\mathbf{x},t),$ and the kinetic energy respects the appropriate symmetry:

$$(\mathcal{D}_\mu\psi)\,(\mathcal{D}_\mu\psi)^* = (\mathcal{D}_\mu\psi')\,(\mathcal{D}_\mu\psi')^*$$

Note the steps involved: ***hypothesize*** a new symmetry of nature (quarks' *color charge* can be *permuted* while leaving total color charge *neutral*); then ***invent*** a whole new type of particle (the ***gluon***) whose properties are fixed by the specific symmetry they are imagined to protect.

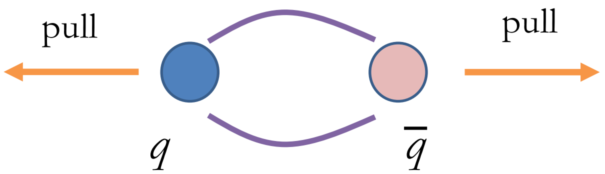
$$\partial_\mu F(\mathbf{x},t) \equiv \left(\frac{\partial}{\partial t}F(\mathbf{x},t), \vec{\nabla}F(\mathbf{x},t)\right)$$

Free Quarks?

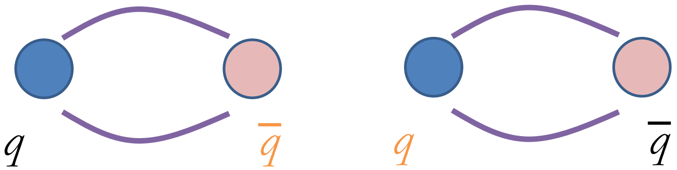
The symmetry of QCD is more complicated than that of QED, and therefore the properties of the *gluons* are more complicated than those of the *photon*. In particular, unlike photons, *gluons can interact with other gluons.*

The fact that gluons can attract other gluons as well as quarks means that the force between quarks *grows* with distance, rather than getting weaker across longer distances.

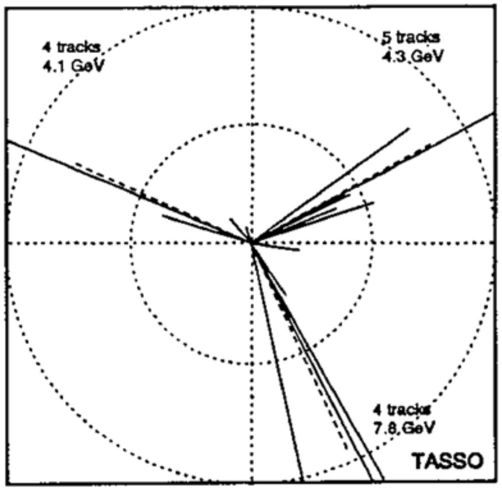
The QCD force between two quarks behaves (sort of) like a *rubber band*: one needs to expend *more* energy the further one wants to stretch two quarks apart.



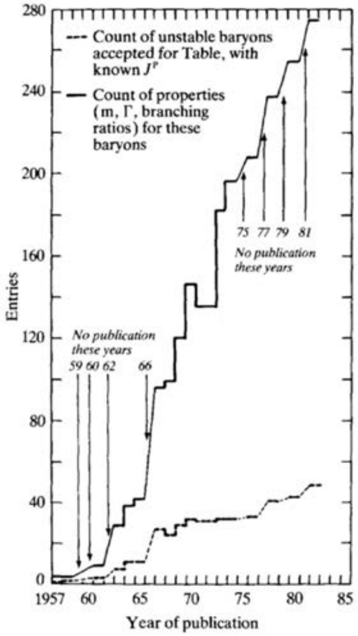
The external energy will *create* a quark-antiquark pair once $\Delta E = 2mc^2$, preserving the QCD color symmetry:



"*jets*" first detected in 1982.



Quarks and QCD: Summary



Whereas some particle physicists (such as *Geoffrey Chew*) responded to the postwar "particle zoo" by focusing on *self-consistent dynamics*, others (including *Murray Gell-Mann*) returned to a prewar emphasis upon *internal symmetries* and *classification.*

Gell-Mann first began grouping particles into "families" in terms of *hypercharge* and *isospin*. These patterns suggested "missing" particles, such as the Ω^-. In 1964, Gell-Mann and Zweig then *tentatively* suggested that the patterns were consistent with groupings of a small set of fundamental particles ("*quarks*" or "*aces*")—though these hypothetical particles would have *fractional charge* and seemed to *violate* the Pauli exclusion principle.

The SLAC-MIT experiments of 1967-69 suggested evidence of *internal structure* within protons, though even Gell-Mann remained ambivalent about whether "partons" were actually physical "quarks."

Only with the advent of *quantum chromodynamics* (1972-74), and evidence of new phenomena such as "*jets*" (1982) did the case for quarks seem compelling for most of the community.

STS.042J / 8.225J Einstein, Oppenheimer, Feynman: Physics in the 20th Century
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