From Quarks
to Quantum Chromodynamics

Workshop on "Half a Century of QCD"

13th Int. Conference on New Frontiers in Physics

Kolymbari, August 28th, 2024

Willibald Plessas

Institute of Physics, University of Graz

Contents

- ❖ A few historical remarks

  Quarks and aces (1964)

- ❖ Special Unitary Symmetries *SU(3)*, *SU(4)*, …
- ❖ Partons ($\gtrsim$ 1968)
- ❖ Quest for strong-interaction dynamics ~1972/73
- ❖ Quantum chromodynamics (QCD)
- ❖ Expectations from QCD

  Particle physics, nuclear physics, heavy-ion physics, …,

  and beyond

1964: Quarks

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

Introduced ***SU(3)*** triplets with fractional charges as fundamental objects: **Quarks**

Murray Gell-Mann, 1929 – 2019

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 (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) 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**.

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6) James Joyce, Finnegan's Wake (Viking Press, New York, 1939) p.383.

„Three quarks for Muster Mark!
Sure he has not got much of a bark.
And sure any he has it's all beside the mark."

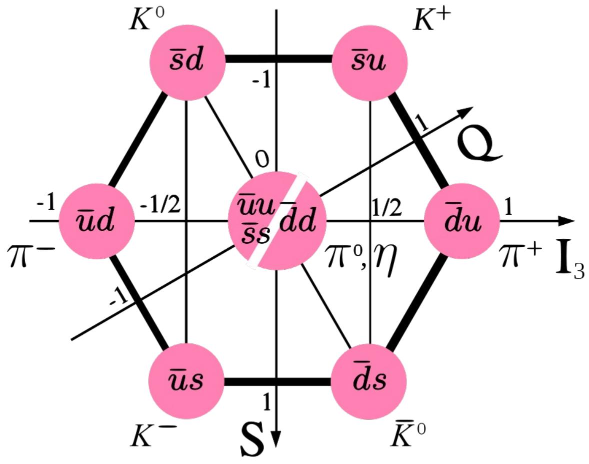
Hadron Multiplets

Mesons

1:

η'

8:

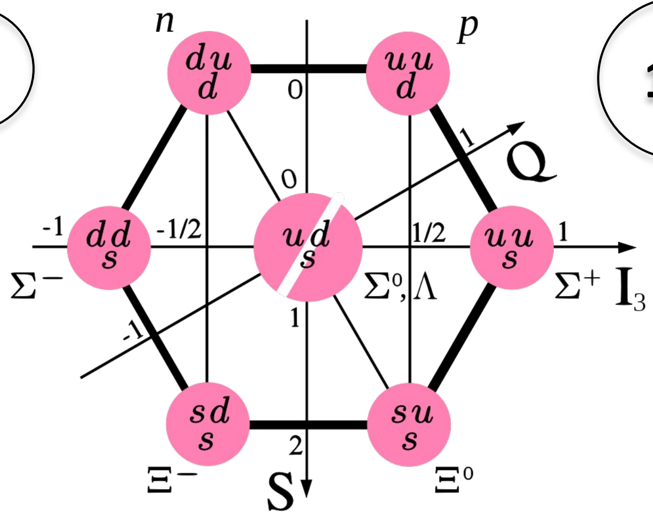


Baryons

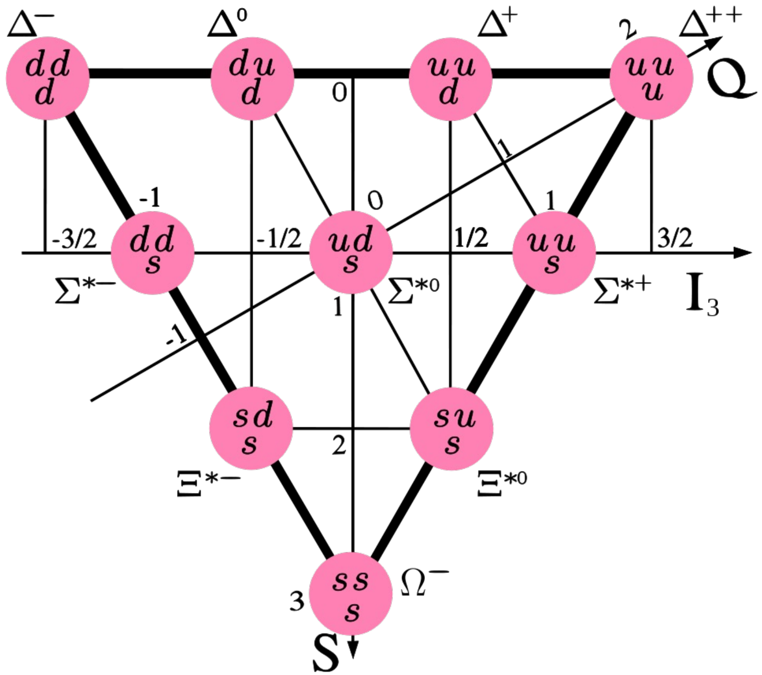
1:

Λ^0 (uds)

8:

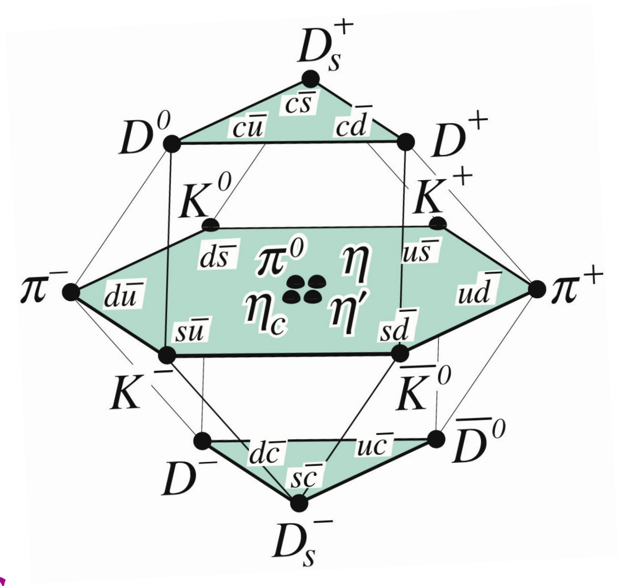


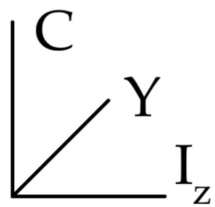
10:

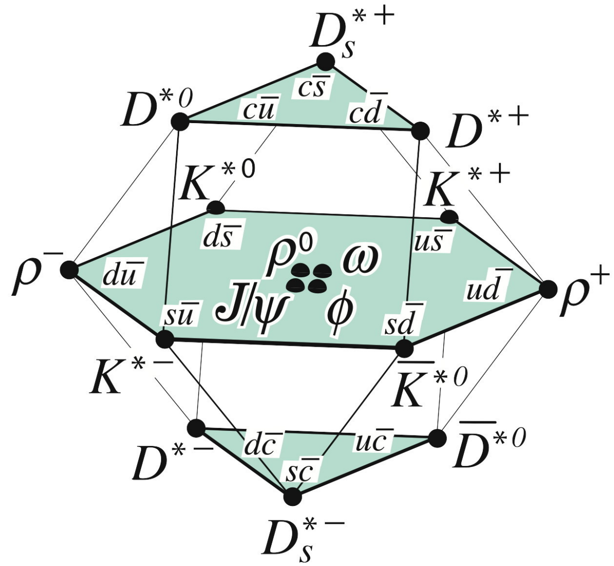


Hadron Multiplets in *SU(4) u, d, s, c*

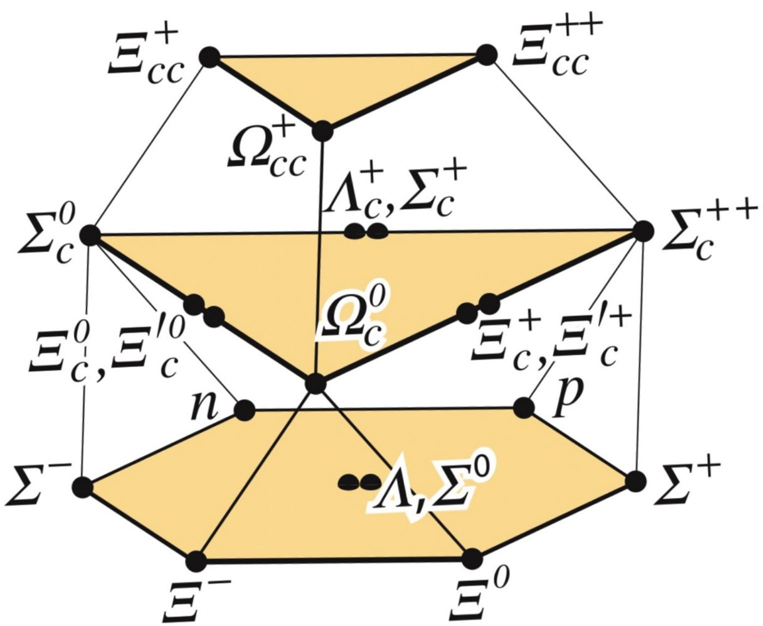
Mesons

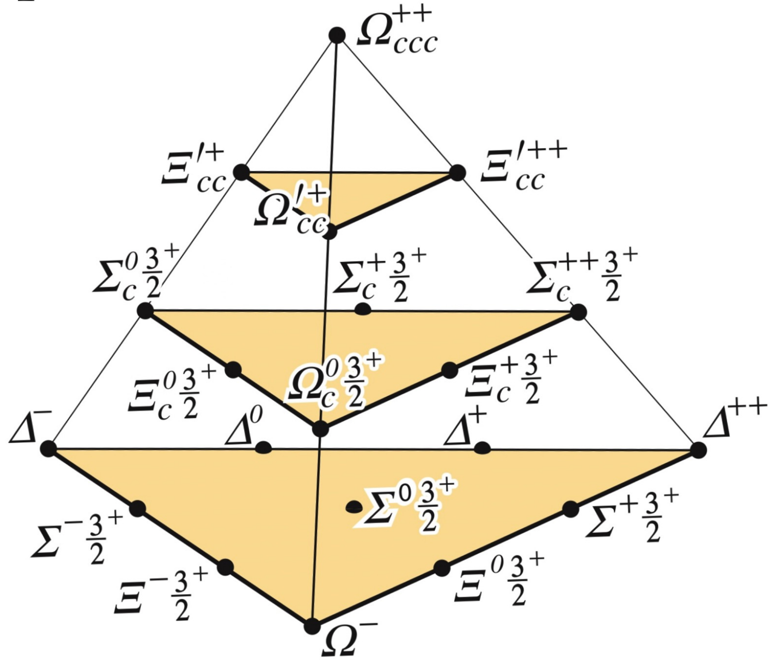






Baryons





George Zweig: “Aces” (1964)

George Zweig @Oberwölz-Symposium
Austria, 2012

ES

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

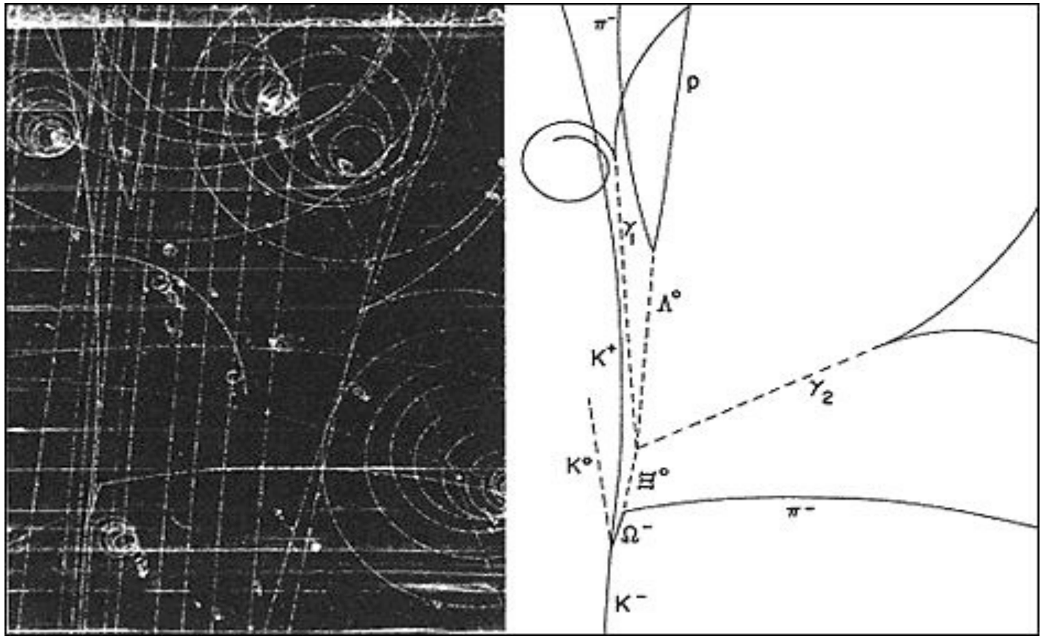
G. Zweig *)
CERN - Geneva

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.

Quarks – Images of Underlying Symmetries

SU(3) symmetry considerations had led Gell-Mann, Ne'eman, and Zweig independently to manifest hadron multiplets – and to predict the **Ω^-** particle.

Still in 1964 this particle was found by Nicholas Samios et al. at the Brookhaven National Laboratory (BNL):



Nicholas Samios

Murray Gell-Mann received the Nobel Prize in 1969:
"for his contributions and discoveries concerning the classification of elementary particles and their interactions".

1968: Substructure of the Proton

In ~1968 the substructure of the proton was revealed experimentally at the Stanford Linear Accelerator Center (SLAC).

First public notice @14th Int. Conf. on High-Energy Physics Vienna 1968

Contribution no. 563 "**Inelastic Electron Scattering from Protons**"
by R.E. Taylor (SLAC), J.I. Friedman, H.W. Kendall (MIT) et al. (unpublished)

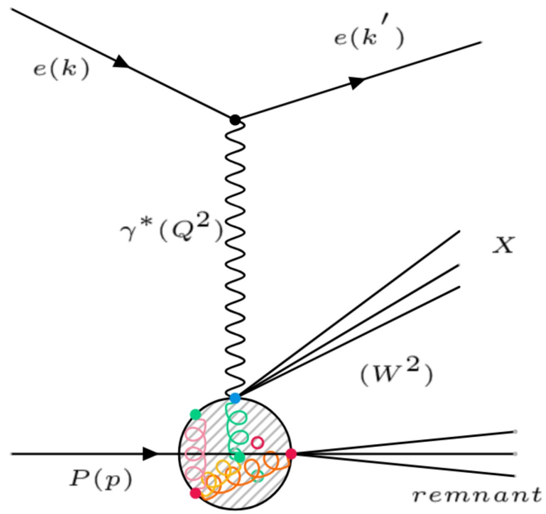
(532)
Photoproduction of π^+ mesons at backward angles between 0.9 GeV and 3.0 GeV
Alvarez R.A., Cooperstein G., Kalata K., Lanza R.C., Luckey D. (MIT)
(Abstract)

(563)
Inelastic scattering from protons
Bloom E., Coward D., DeStaebler H., Drees J., Litt J., Miller G., Mo L., Taylor R.E. (SLAC), Breidenbach M., Friedman J.I., Kendall H.W. (MIT), Loken S. (Cal. Tech.)
(Abstract)

(565)
Multibody photoproduction from hydrogen with 16 GeV bremsstrahlung
Davier M., Derado I., Drickey D., Fries D., Mozley R., Odian A., Villa F., Yount D., Zdanis R. (SLAC)

W.K.H. Panofsky:
Proceedings of the 14th Int. Conf. on High-Energy Physics, Vienna, 1969

Ed. by J. Prentki and J. Steinberger
CERN Sci. Inf. Service, Geneva, 1968, p. 23



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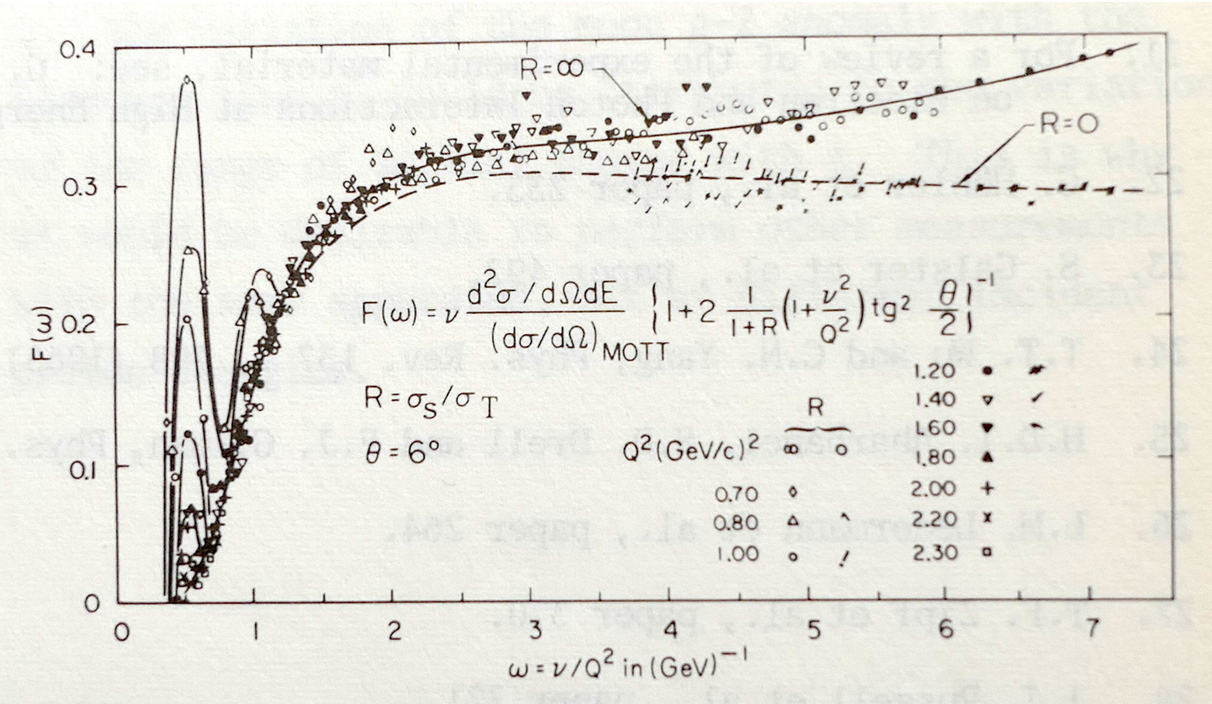


$F(\omega) = \nu\, W_2(q^2,\nu)$ as a function of $\omega=\nu/q^2$

<u>Rapporteur W.K.H. Panofsky:</u>

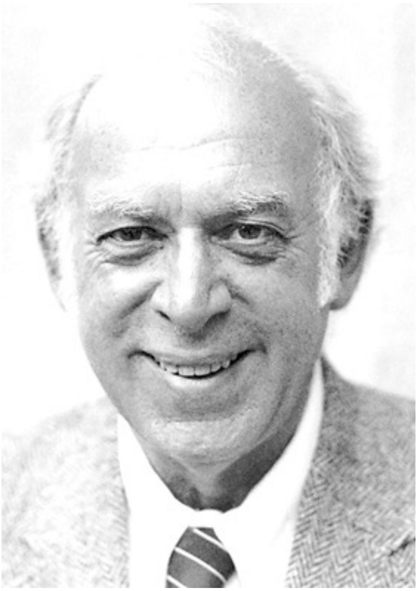
Theoretical speculations are focused on the possibility that these data might give evidence on the point-like charged structures within the nucleon.

However a great deal more fundamental experimental material must be developed before a clear picture can emerge.

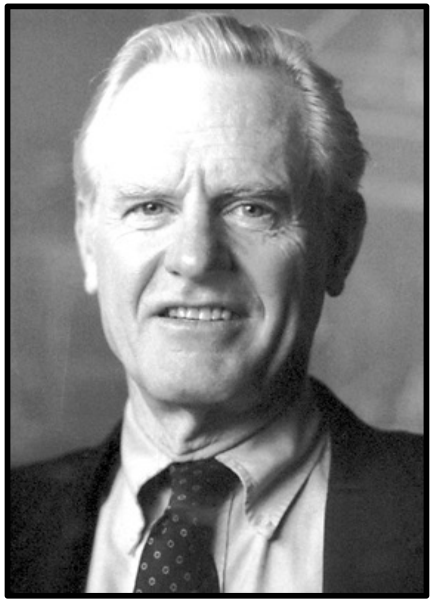
1968: Substructure of the Proton – Partons

The proton (like all other hadrons) consists of parts, the partons (R.P. Feynman and J.D. Bjorken).

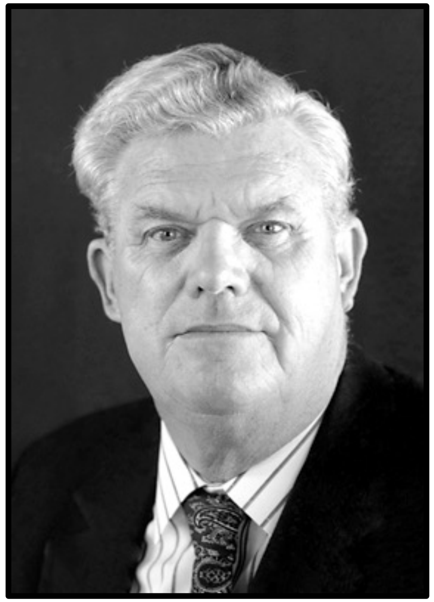
Nobel Prize in 1990 to: J.I. Friedman, H.W. Kendall and R.E. Taylor:
"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics".



J.I. Friedman, 1930 –



H.W. Kendall, 1926 – 1999



R.E. Taylor, 1929 – 2018

1964 – 1968 – 1972 What are Quarks?

- Are quarks particles or just images of symmetries?
- If quarks are particles with spin, which statistics do they follow?
- Can particles/quarks with fractional charges be observed?
- If quarks are particles, what are their interactions?
- Which dynamics keeps hadrons together?

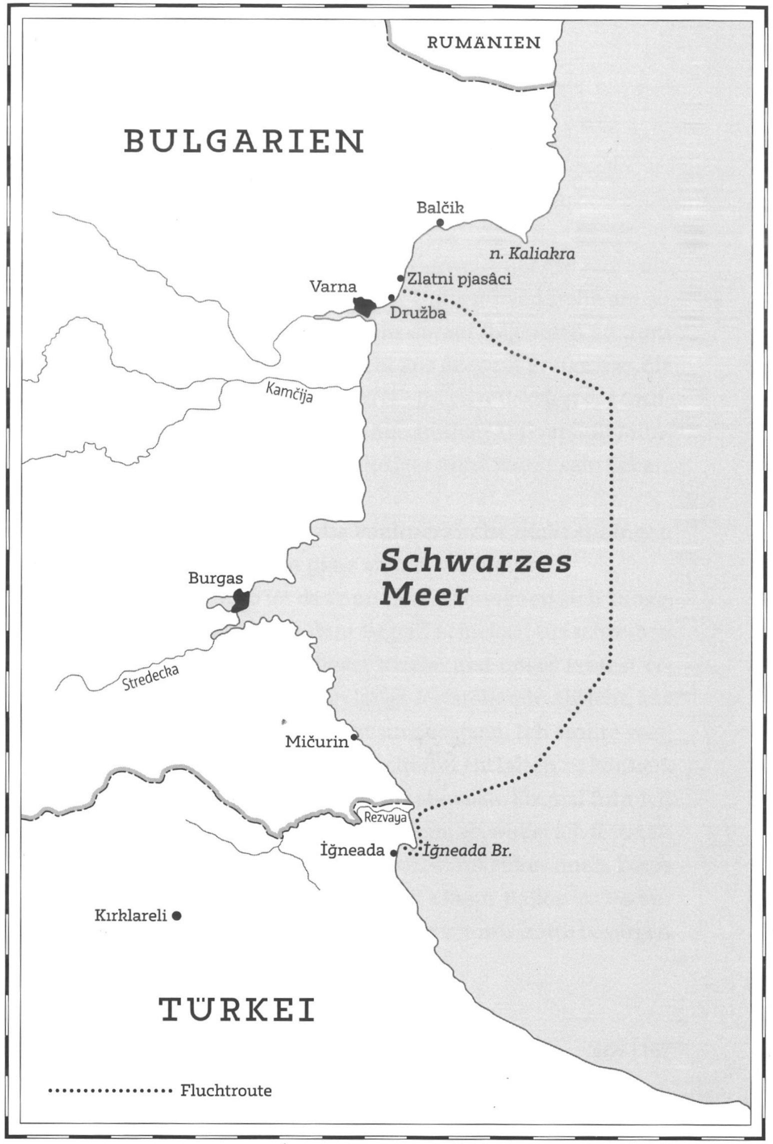
M. Gell-Mann @Schladming Winter School 1972:

Current and constituent quarks

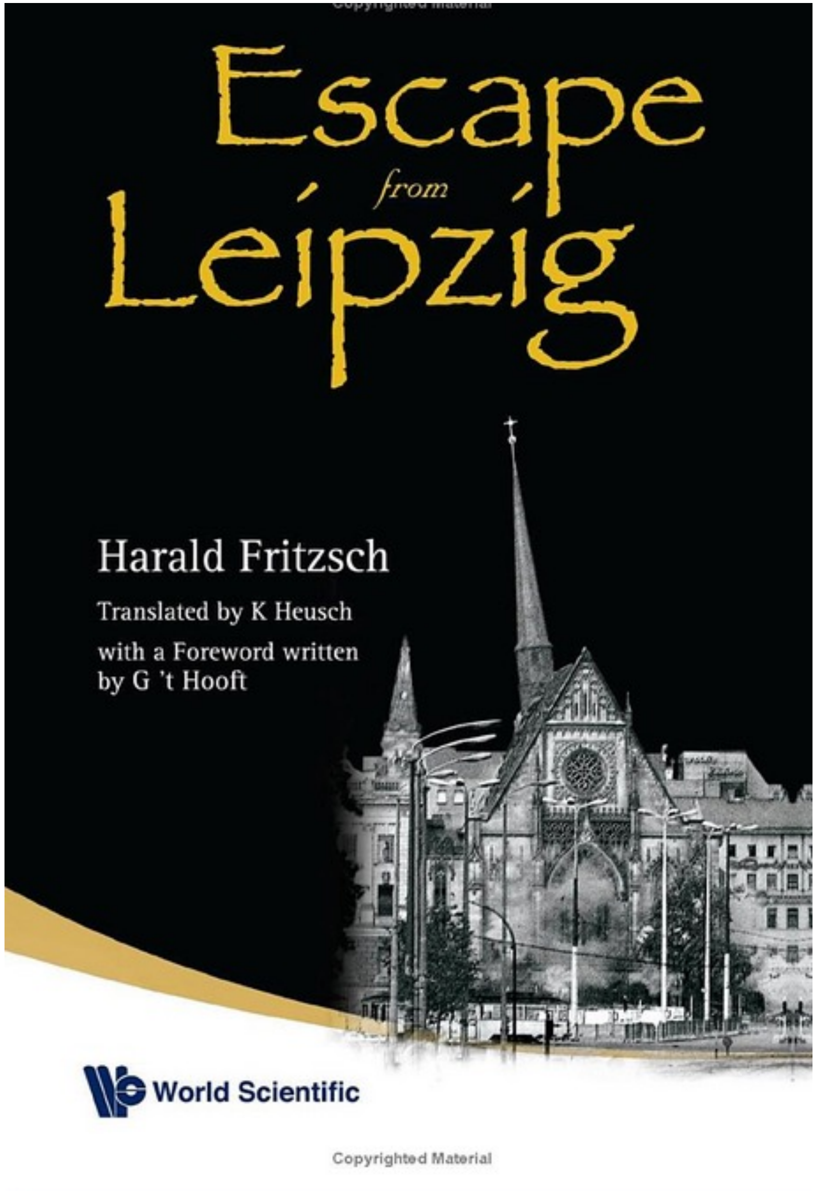
Schladming Winter School 1972

F.l.t.r.: M. Gell-Mann, A. Bartl, P. Breitenlohner, H. Fritzsch, H. Kleinert, P. Urban

1968: Fritzsch's Escape from Leipzig



Escape route July 25th/26th, 1968



1972 – 1973: Emergence of QCD

Current Algebra: Quarks and What Else?

Harald Fritzsch*†

and

Murray Gell–Mann**†

CERN, Geneva, Switzerland

Proceedings of the XVI International Conference on High Energy Physics, Chicago, 1972. Volume 2, p. 135 (J. D. Jackson, A. Roberts, eds.)

Volume 47B, number 4 PHYSICS LETTERS 26 November 1973

ADVANTAGES OF THE COLOR OCTET GLUON PICTURE☆

H. FRITZSCH*, M. GELL-MANN and H. LEUTWYLER**

California Institute of Technology, Pasadena, Calif. 91109, USA

Received 1 October 1973

It is pointed out that there are several advantages in abstracting properties of hadrons and their currents from a Yang–Mills gauge model based on colored quarks and color octet gluons.

Colored Quarks and Gluons: QCD

$$L = \bar{q}\left[i\gamma_\mu \left(\partial^\mu + ig\frac{\lambda^a}{2} A_a^{\ \mu}\right) - m \right] q - \frac{1}{4} G^a_{\ \mu\nu} G_a^{\ \mu\nu}$$

quark fields

gluon fields

quark fields

gluon field-strength tensor

$$G_{\mu\nu}^{\ \ a} = \partial_\mu A_\nu^{\ a} - \partial_\nu A_\mu^{\ a} + g f_{abc} A_\mu^{\ b} A_\nu^{\ c}$$

gluon self-interaction

➤ Non-Abelian gauge theory in $SU(3)_C$

QCD: Millenium Prize Problem

Clay Mathematics Institute

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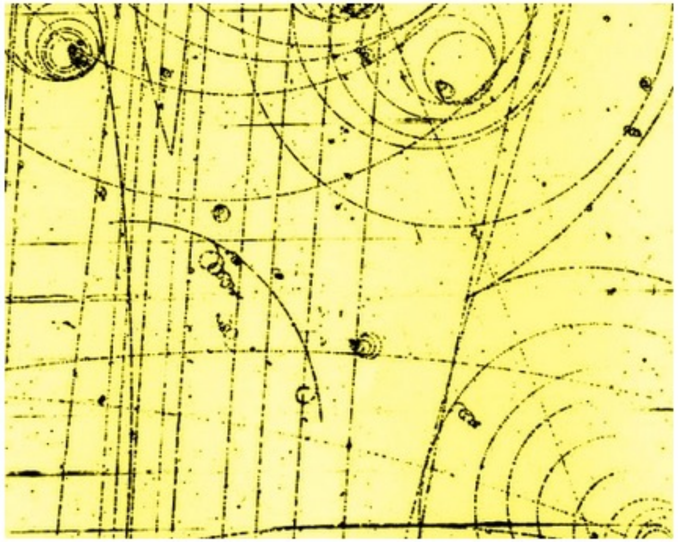
Quantum Young-Mills theory and the mass gap

The laws of quantum physics stand to the world of elementary particles in the way that Newton's laws of classical mechanics stand to the macroscopic world. Almost half a century ago, Yang and Mills introduced a remarkable new framework to describe elementary particles using structures that also occur in geometry. Quantum Yang-Mills theory is now the foundation of most of elementary particle theory, and its predictions have been tested at many experimental laboratories, but its mathematical foundation is still unclear. The successful use of Yang-Mills theory to describe the strong interactions of elementary particles depends on a subtle quantum mechanical property called the "mass gap": the quantum particles have positive masses, even though the classical waves travel at the speed of light. This property has been discovered by physicists from experiment and confirmed by computer simulations, but it still has not been understood from a theoretical point of view. Progress in establishing the existence of the Yang-Mills theory and a mass gap will require the introduction of fundamental new ideas both in physics and in mathematics.



https://www.claymath.org/millennium/yang-mills-the-maths-gap/

QCD Properties and Its Solution

A comprehensive solution of QCD must incorporate the following properties:

- It must have a mass gap, i.e. any vacuum excitation must produce $\Delta > 0$

  (in order to lead to strong but short-ranged nuclear forces).

- It must produce quark confinement

  (in order to guarantee all hadrons to be color singlets – no free quarks).

- It must lead to asymptotic freedom

  (interaction-free for $E \longrightarrow \infty$).

- It must exhibit (spontaneous) chiral-symmetry breaking

  (in order to produce hadrons of non-zero masses)

- It must, of course, describe all hadron phenomenology consistently, at all energies

  (in order to be a practical theory of strong forces).

Solution Methods for QCD

- Perturbative QCD (for $E \longrightarrow \infty$)
- QCD on a space-time lattice
- Effective field theories, in particular, chiral perturbation theory
- Functional methods

  Dyson-Schwinger equations (DSE)

  Functional renormalization group (FRG)
- Effective / Constituent quark models
- ….

Half a Century Has Passed

The present workshop will specifically address:

- Perturbative QCD in the high-energy regime – *Johannes Blümlein*
- Changing symmetry properties at different energies (temperaturs) – Leonid Glozman
- Embedding QCD into "wider" symmetries – *Stan Brodsky and Mikhail Shifman*
- Chiral dynamics and low-energy QCD – *Evgeny Epelbaum* and *Anthony Thomas*
- Hadron Spectroscopy from effective approaches – Paul Hoyer and Willibald Plessas
- Solving QCD on a lattice – *Constantia Alexandrou* and *Padmanath Madanagopalan*
- Hadron structure (e.m., weak, gravitational) – *Constantia Alexandrou* and Willibald Plessas
- QCD in dense matter – Sonia Kabana and *David Blaschke*