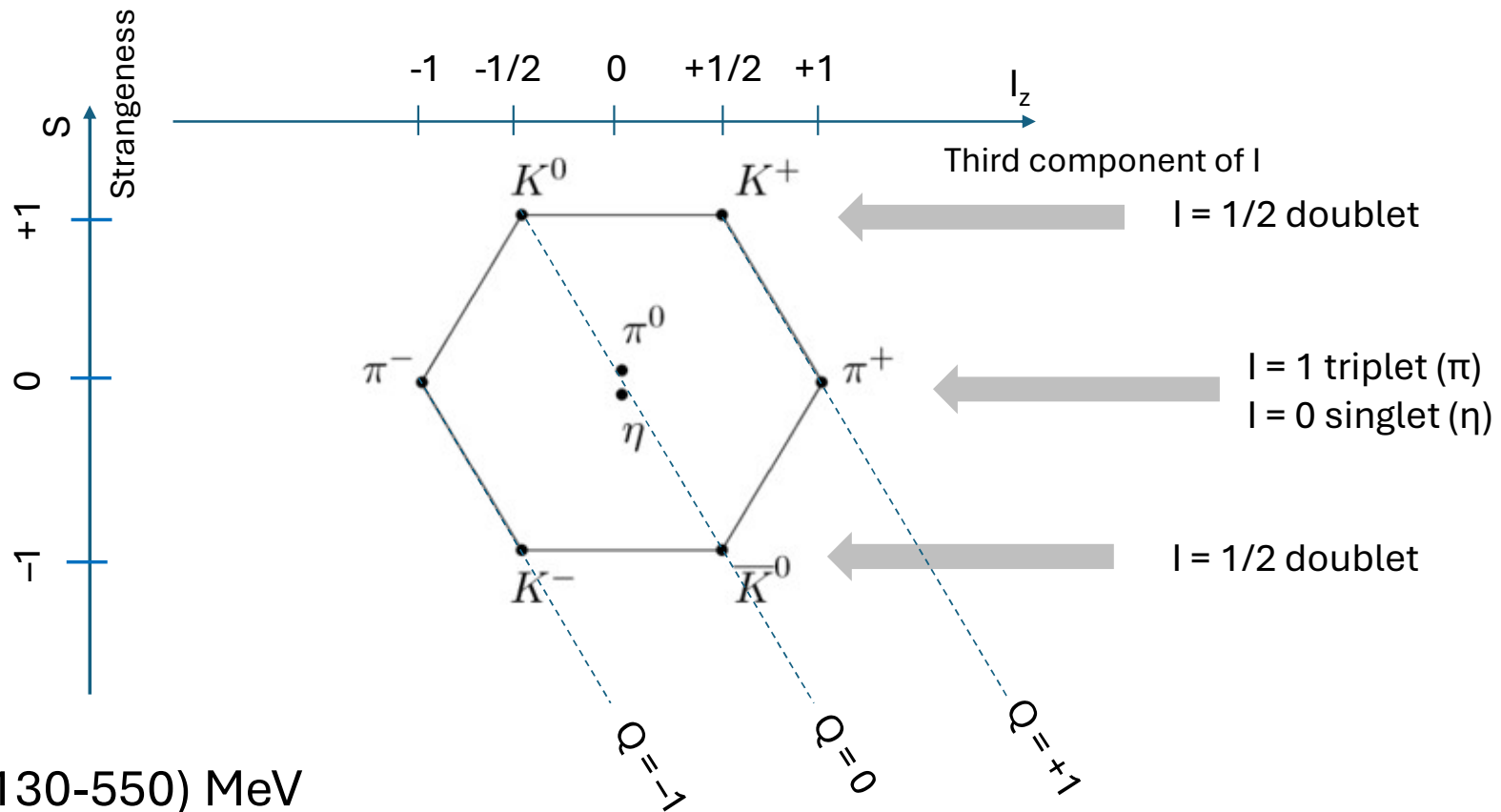


A black and white photograph of The Beatles performing on stage. John Lennon is on the left, playing a hollow-body electric guitar. Paul McCartney is in the center, singing and playing a bass guitar. George Harrison is on the right, playing a hollow-body electric guitar. Ringo Starr is in the foreground, partially obscured, playing the drums. The background features a large, circular, metallic structure with many small lights.

Quarks (1962-1995)

M.Sozzi - Fundamental Interactions - Università di Pisa

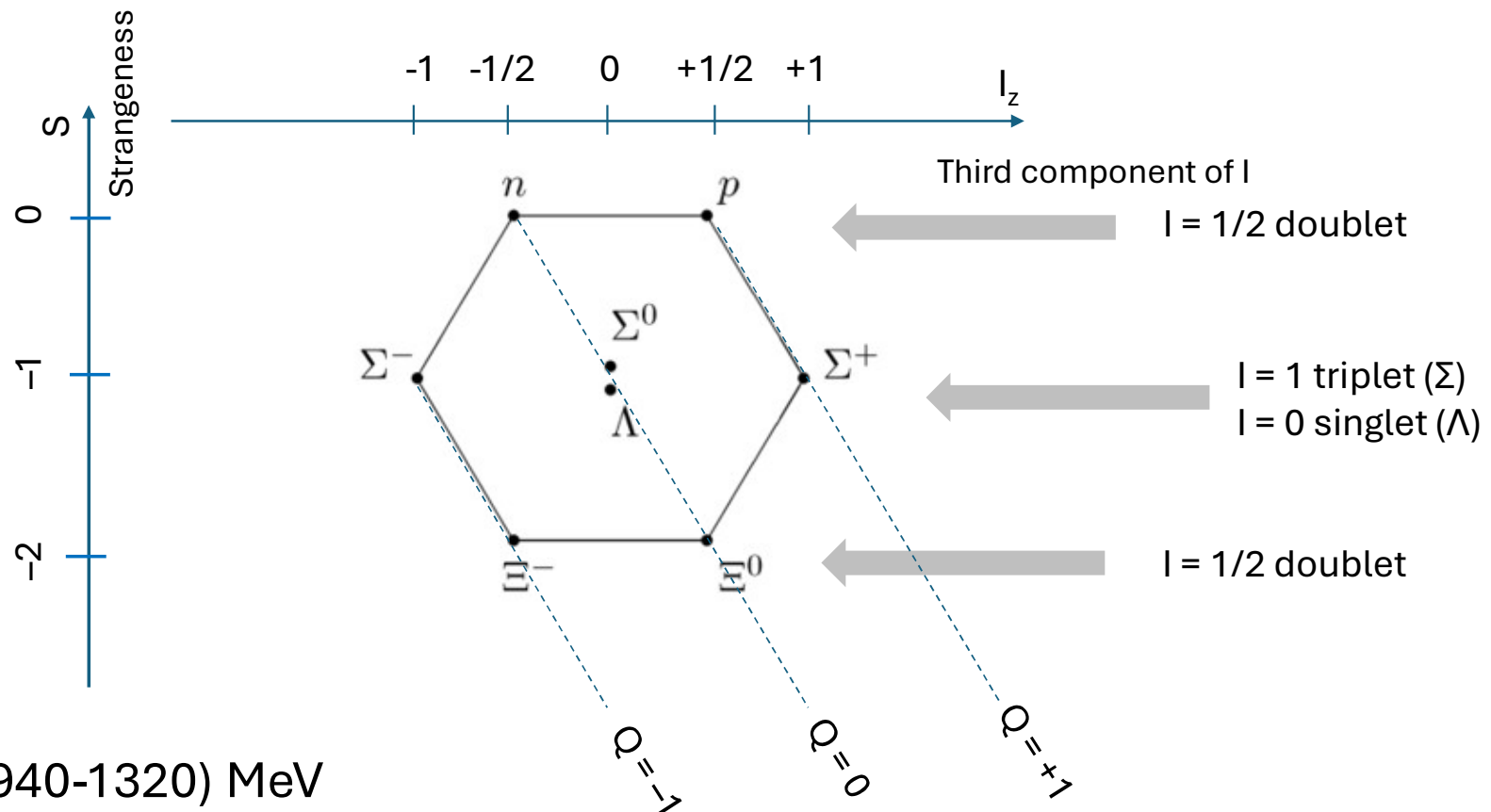
Hadrons (1)



Masses: O(130-550) MeV

Octet of pseudo-scalar mesons

Hadrons (2)



Masses: O(940-1320) MeV

Octet of spin-1/2 baryons (and antioctet)

The "eightfold way"

1961 Pasadena, London



1969

Murray Gell-Mann
(1929-2019)



Yuval Ne'eman
(1925-2006)

CALIFORNIA INSTITUTE OF TECHNOLOGY

Synchrotron Laboratory
Pasadena, California

THE EIGHTFOLD WAY:

A THEORY OF STRONG INTERACTION SYMMETRY*

Murray Gell-Mann

March 15, 1961

(Preliminary version circulated Jan. 20, 1961)

8.B

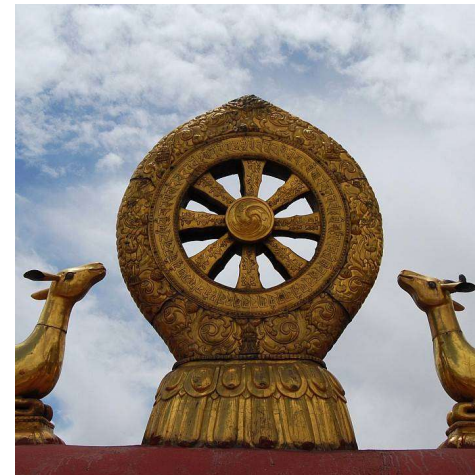
Nuclear Physics 26 (1961) 222—229; © North-Holland Publishing Co., Amsterdam
Not to be reproduced by photoprint or microfilm without written permission from the publisher

DERIVATION OF STRONG INTERACTIONS FROM A GAUGE
INVARIANCE

Y. NE'EMAN

Department of Physics, Imperial College, London

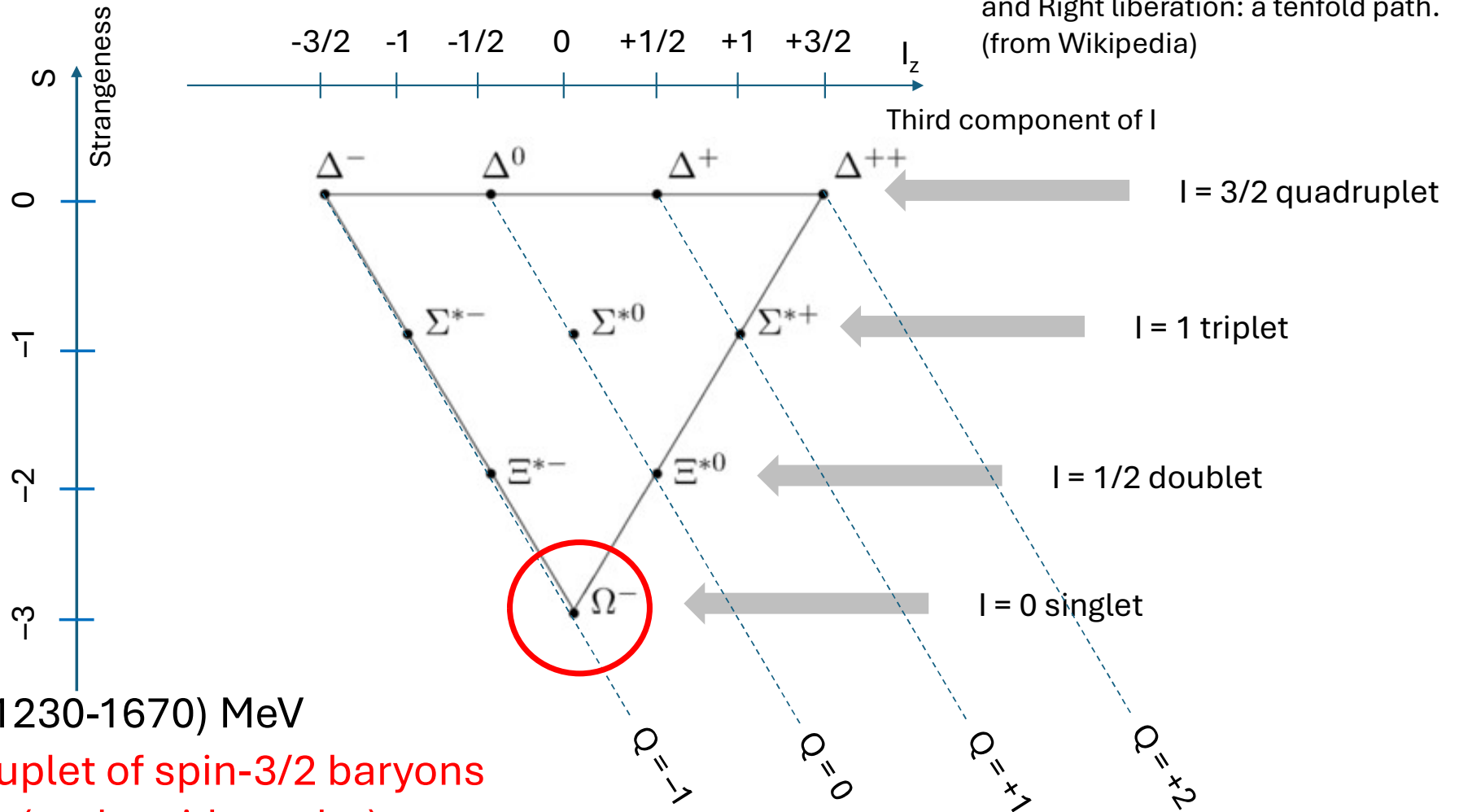
Received 13 February 1961



Right View
Right Resolve
Right Speech
Right Conduct
Right Livelihood
Right Effort
Right Mindfulness
Right *samadhi*

Hadrons (3)

Cultivation of the noble eightfold path of a learner leads to the development of two further paths: Right knowledge and Right liberation: a tenfold path. (from Wikipedia)



Masses: O(1230-1670) MeV

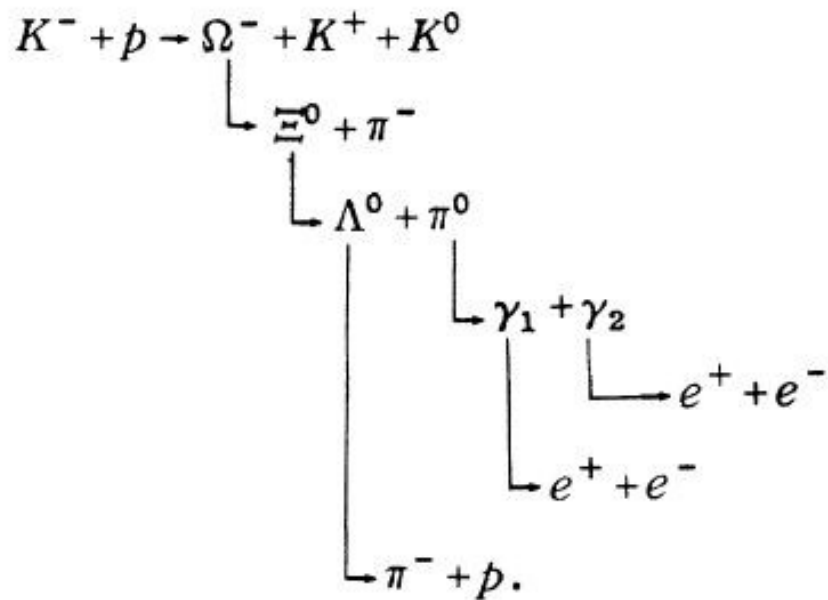
Decuplet of spin-3/2 baryons
(and antidecuplet)

The Ω^-

1961 Brookhaven

5 GeV K^- secondary beam,

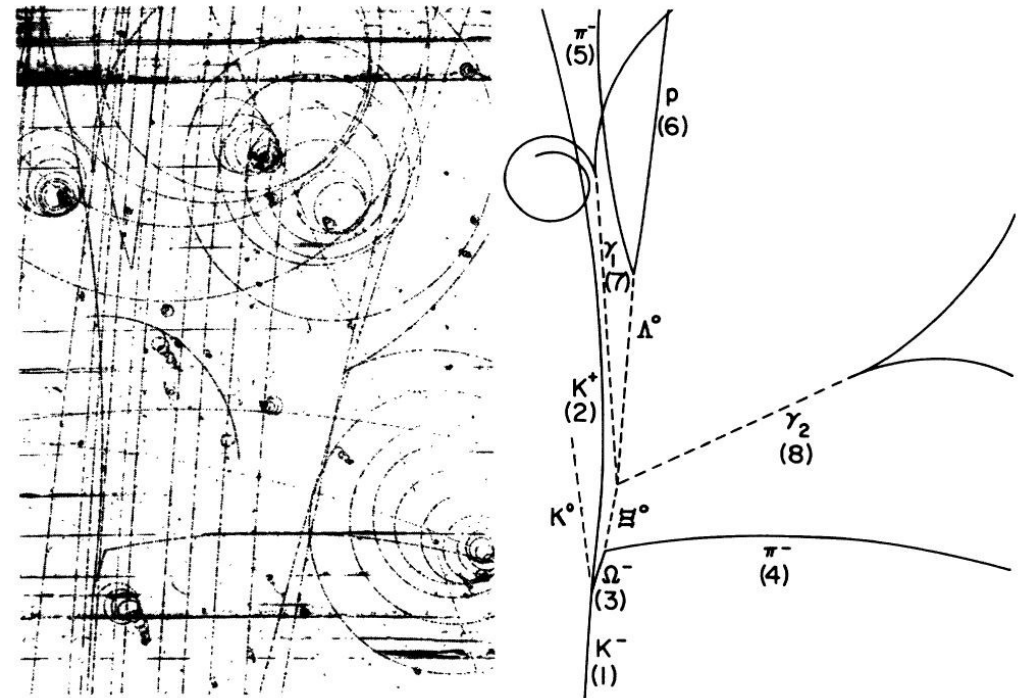
2m bubble chamber, 100000 pictures



1686 MeV, charge -1 , strangeness -3

OBSERVATION OF A HYPERON WITH STRANGENESS MINUS THREE*

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



Quarks (1)

Phys.Lett. 8 (1964) 214

1964 Pasadena

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

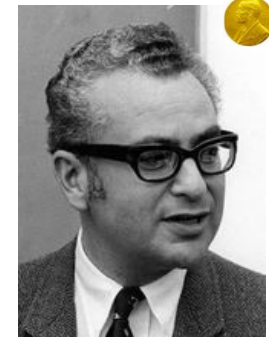
Received 4 January 1964

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

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 b^0 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 (qqq) , $(qqq\bar{q})$, 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**.



1969

Murray Gell-Mann
(1929-2019)

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.
But O, Wreneagle Almighty, wouldn't un be
[a sky of a lark
To see that old buzzard whooping about
[for uns shirt in the dark
And he hunting round for uns speckled
[trousers around by Palmerstown Park?

J. Joyce – Finnegans Wake (1939)

Aces (2)

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.

8182/TH.401

17 January 1964

1964 CERN



George Zweig
(1937-)

I didn't know how many aces there were. Aces were represented graphically as regular polygons of increasing size, corresponding to increasing mass. Aces were fundamental point particles like leptons, and like leptons they had fields that entered into the electromagnetic and weak currents. Therefore I guessed that the number of aces would equal the number of leptons. Since four leptons were known at the time, I called them aces. I should have called them dice.

(G. Zweig, 2013)

The quark model

The hadron multiplets can be described as built of three fundamental entities

Three "flavours" of quarks: **up, down, strange** ("sideways"):

- fractional electric charge: **+2/3 (u)** or **-1/3 (d,s)**
- baryon number 1/3
- (u,d) form a **isospin 1/2** doublet
- s has **isospin 0** but **strangeness -1**
- antiquarks have opposite quantum numbers

Mesons are composed of a quark and an antiquark

Baryons are composed of three quarks

(and anti-baryons of three antiquarks)

$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^0
$u\bar{d}$	1	0	π^+
$d\bar{u}$	-1	0	π^-
$d\bar{d}$	0	0	η
$u\bar{s}$	1	1	K^+
$d\bar{s}$	0	1	K^0
$s\bar{u}$	-1	-1	K^-
$s\bar{d}$	0	-1	$\bar{K}^0$
$s\bar{s}$	0	0	η'

Pseudo-scalar
meson octet

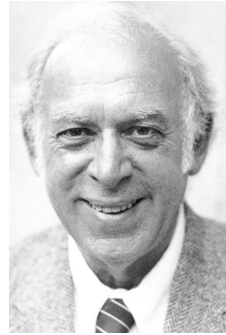
qqq	Q	S	Baryon	
uuu	2	0	Δ^{++}	N/A
uud	1	0	Δ^+	p
udd	0	0	Δ^0	n
ddd	-1	0	Δ^-	N/A
uus	1	-1	Σ^{*+}	Σ^+
uds	0	-1	Σ^{*0}	Σ^0, Λ
dds	-1	-1	Σ^{*-}	Σ^-
uss	0	-2	Ξ^{*0}	Ξ^0
dss	-1	-2	Ξ^{*-}	Ξ^-
sss	-1	-3	Ω^-	N/A

Baryon
octet

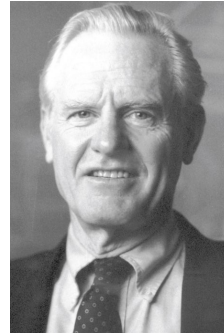
Baryon
decuplet

Partons

1968-69 Stanford
Deep-inelastic
scattering of e^- on p



Jerome Friedman
(1930-)



Henry Kendall
(1926-1999)



Richard Taylor
(1929-2018)

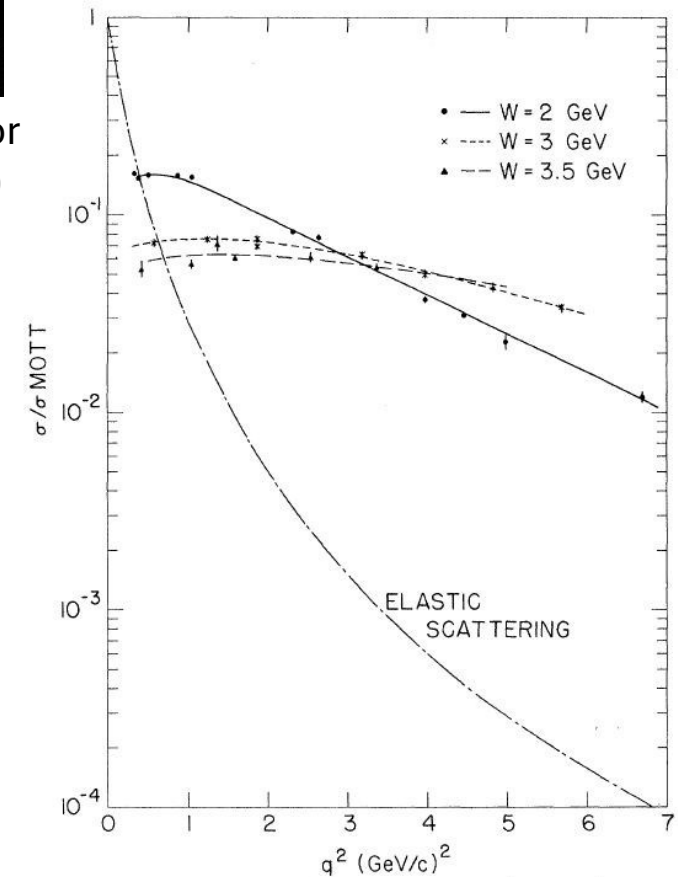


1990



7-21 GeV electrons, fixed angle scattering 6° - 10°

Scaling behaviour of
cross section gives
evidence of point-like
constituents inside
proton



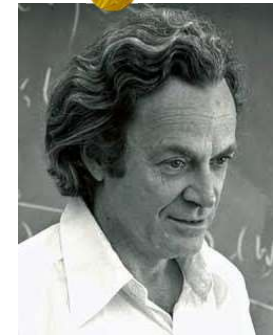
Partons = quarks

R. Feynman (1969): My quarks have small masses, and they do not come apart because of something I'll tell you about 25 years from now. The masses that I want are so low that we would have absolutely definitely seen them. Thus perhaps the whole thing is nonsense, and that experiment will tell us very soon. Or if it is right, then this is very very exciting, because we are approaching a paradox, and the hope of physics is to find a paradox. This is the real way of making a revolution. We have to find a place where we are shocked. And I think we are getting near to one. I hope we are....

Scattering experiments in later years (including neutrino-proton inelastic scattering) showed that partons

- partons have spin $1/2$
- partons have fractional electric charge
- 3 partons carry most of the momentum of proton and neutron

1965



Richard P. Feynman
(1918-1988)

The Behavior of Hadron Collisions at Extreme Energies

RICHARD P. FEYNMAN

California Institute of Technology, Pasadena, California

Talk given at

Third International Conference
on High Energy Collisions

State University of New York, Stony Brook
September 5-6, 1969

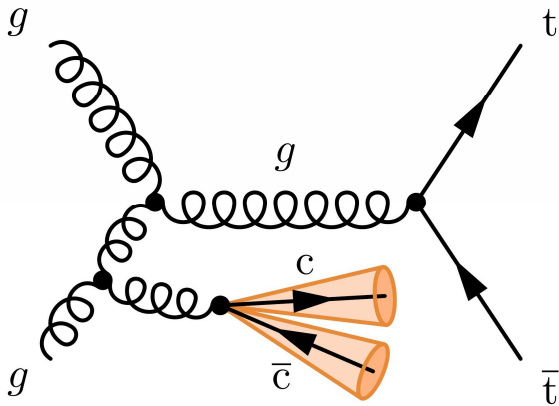
Quark colour, QCD

1964-65

Quarks have "colour"

1973

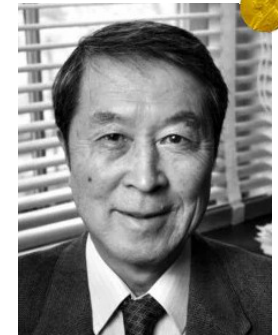
Quarks are "asymptotically free"
at high energies



Oscar W. Greenberg
(1932-)

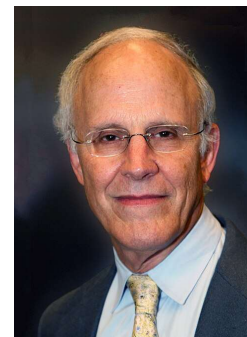


Moo-Young Han
(1934-2016)



Yoichiro Nambu
(1921-2015)

2008



David Gross
(1941-)



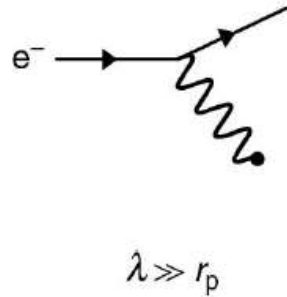
Frank Wilczek
(1951-)



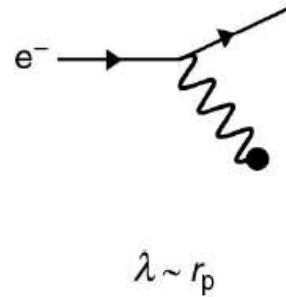
David Politzer
(1949-)

Hadron structure

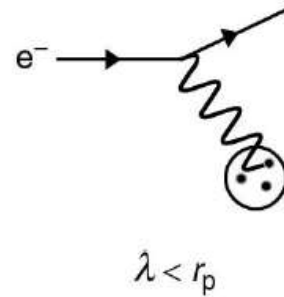
Point charge



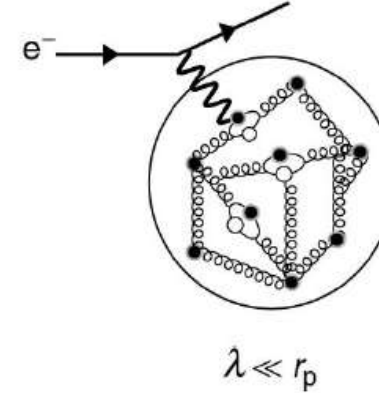
Charged sphere



Three point charges



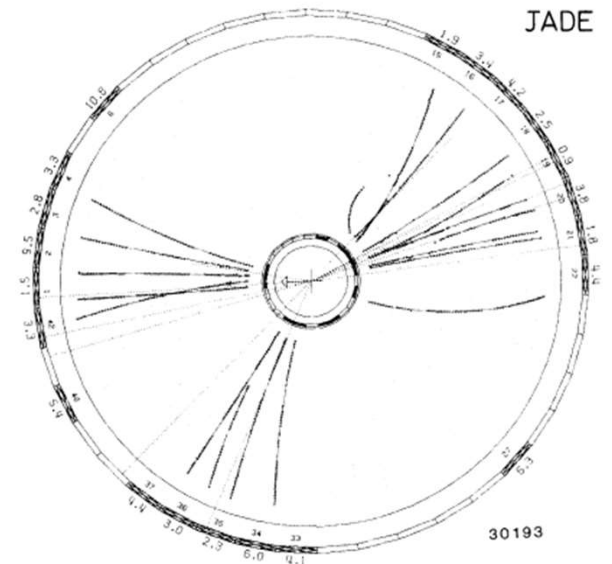
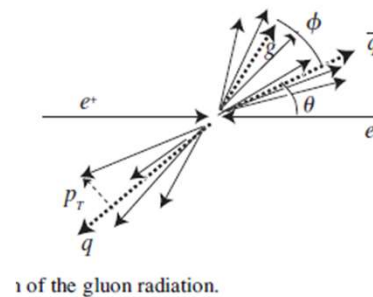
Full internal structure including mediators



Gluons: mediators of the strong force

- coloured, self-interacting
- confined inside hadrons

Quarks and gluons appear as "jets" of particles



Particles 6

Particle	Mass (MeV/c ²)	Charge (e)	Spin ($\hbar/2$)	Lifetime (s)	Decay modes
u	~ 2	+2/3	1/2	N/A	d+...
d	~ 5	-1/3	1/2	N/A	u+...
c	~ 1300	+2/3	1/2	N/A	d,s+...
s	~ 95	-1/3	1/2	N/A	u,d+...
t	~ 173000	+2/3	1/2	N/A	b,s,d+...
b	~ 4200	-1/3	1/2	N/A	c,s,u,d+...

Quarks are never observed as free particles

The November revolution

1974 Brookhaven, Stanford

Experimental Observation of a Heavy Particle J/ψ

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee

Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

J/ψ meson
 $3097 \text{ MeV}/c^2$

J.J. Aubert *et al.* – Phys. Rev. Lett. 33 (1974) 1404
J.E. Augustin *et al.* – Phys. Rev. Lett. 33 (1974) 1406



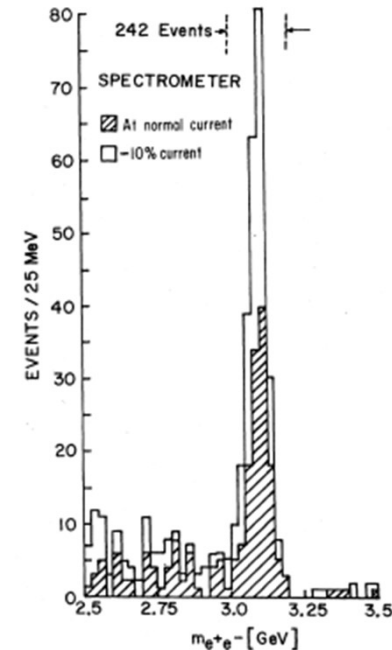
Sam Ting
(1936-)



1976

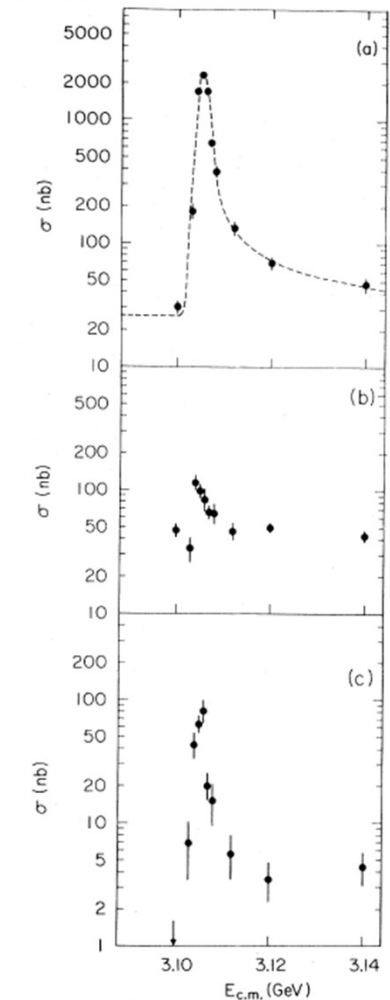


Burton Richter
(1931-2018)



Narrow state
composed of $c\bar{c}$

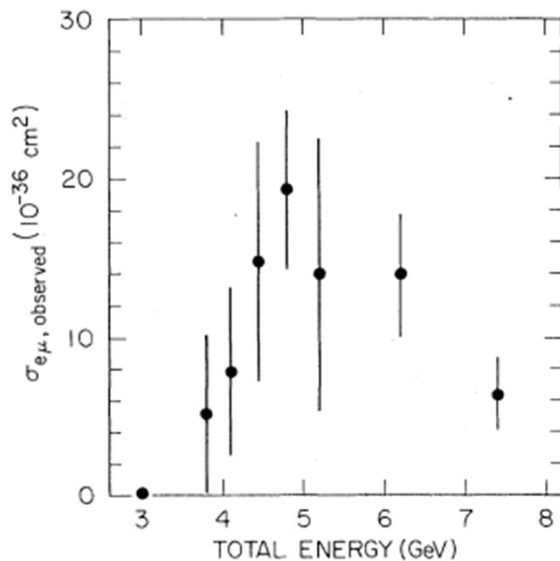
c quark
 $\sim 1.5 \text{ GeV}/c^2$



M.Sozzi - Fundamental Interactions - Università di Pisa

The third generation

1975 Stanford



Tau lepton
1777 MeV/c²

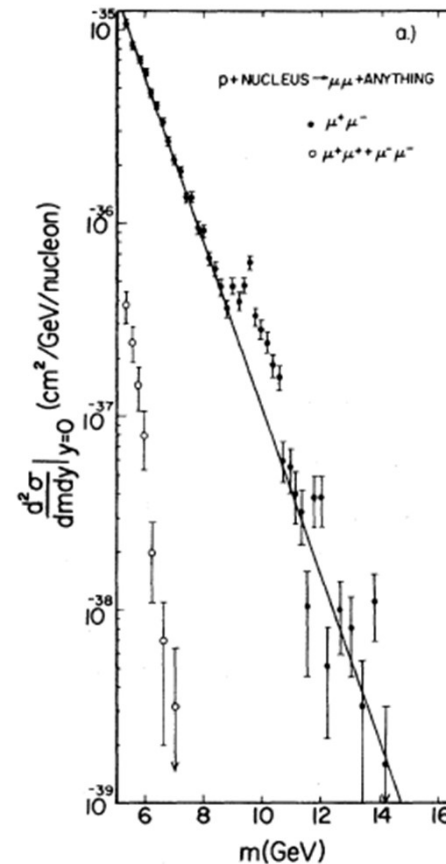
M.L. Perl *et al.* –
Phys. Rev. Lett. 35 (1975) 1489



Martin Perl
(1927-2014)

1982

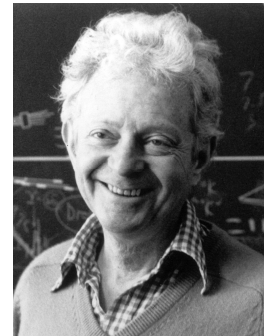
1977 Fermilab



Y meson
narrow state
composed of $b\bar{b}$

b quark
 $\sim 5 \text{ GeV}/c^2$

S.W. Herb *et al.* –
Phys. Rev. Lett. 39 (1977) 252



Leon Lederman
(1922-2018)

M.Sozzi - Fundamental Interactions - Università di Pisa

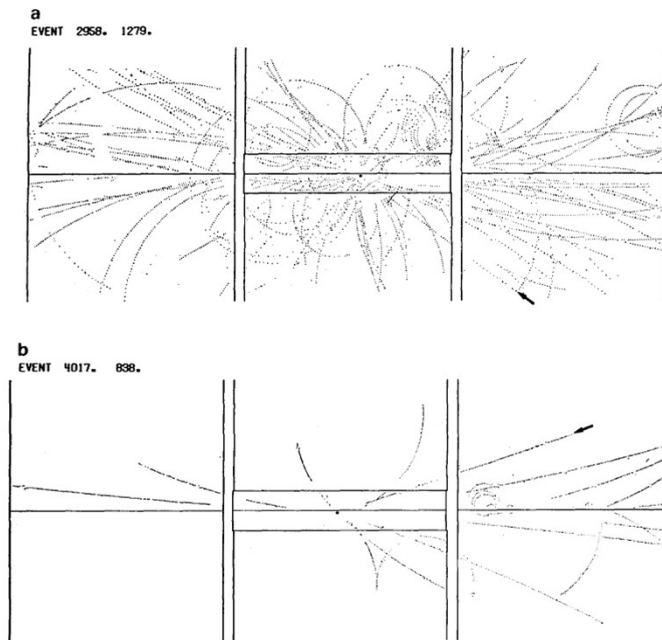
Quark flavours

	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z -component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	+1	0	0
B – bottomness	0	0	0	0	-1	0
T – topness	0	0	0	0	0	+1

Sign of
charge =
sign of
flavor

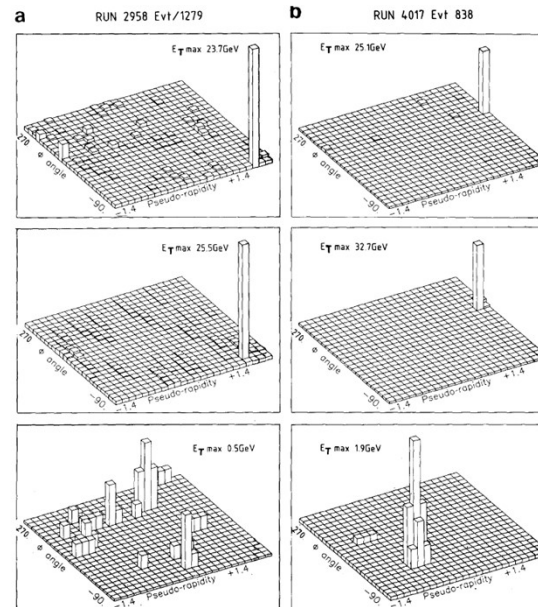
The intermediate vector bosons

1983 CERN



$W^\pm$ boson $80.4 \text{ GeV}/c^2$

Z^0 boson $91.2 \text{ GeV}/c^2$



1984



Carlo Rubbia
(1934-)

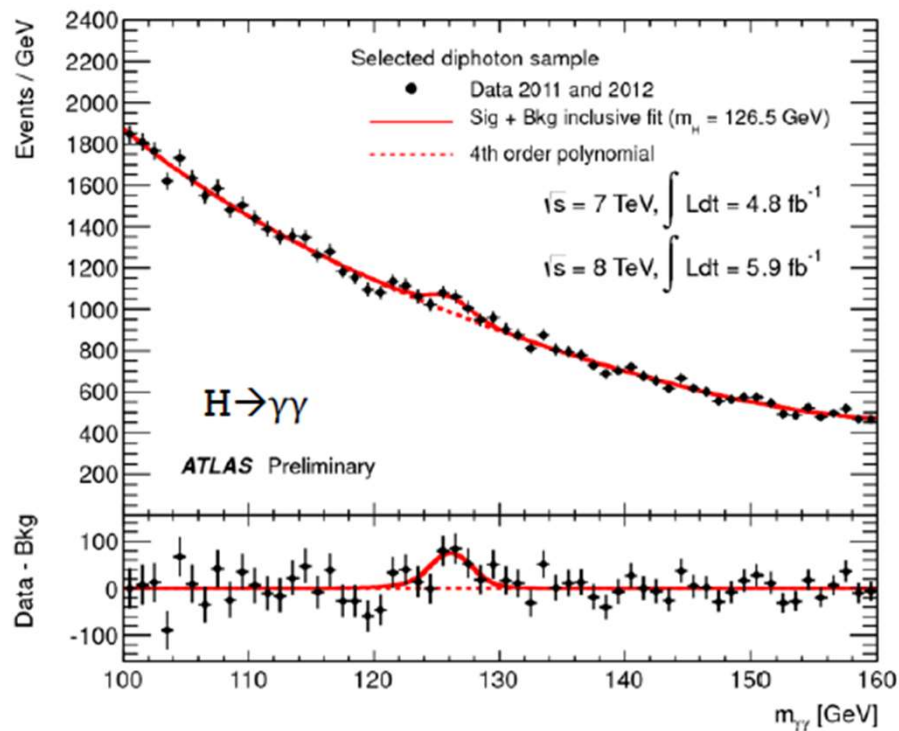


Simon van der Meer
(1925-2011)

Confirmation of the
Glashow-Weinberg-Salam
electro-weak theory

The Higgs boson

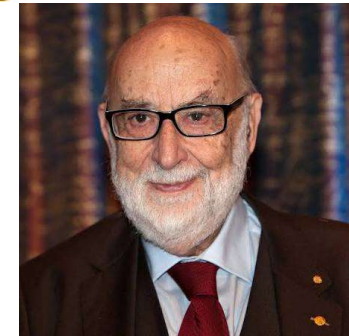
2012 CERN



2013



Peter Higgs
(1929-2024)



Francois Englert
(1932-2026)

& Robert Brout, Gerald Guralnik, Carl Hagen,
Thomas Kibble

H boson $125.4 \text{ GeV}/c^2$

The big picture

three generations of matter (fermions)			interactions / force carriers (bosons)	
QUARKS	I	II	III	
	mass $\approx 2.16 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ u up	mass $\approx 1.273 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ c charm	mass $\approx 172.57 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ t top	0 0 1 g gluon
	mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ d down	mass $\approx 93.5 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ s strange	mass $\approx 4.183 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ b bottom	0 0 1 γ photon
	mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ e electron	mass $\approx 105.66 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ μ muon	mass $\approx 1.77693 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ τ tau	0 1 Z Z boson
	mass $< 0.8 \text{ eV}/c^2$ charge 0 spin $\frac{1}{2}$ ν_e electron neutrino	mass $< 0.17 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ ν_μ muon neutrino	mass $< 18.2 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ ν_τ tau neutrino	0 ± 1 1 W W boson
				0 0 0 H higgs
LEPTONS				GAUGE BOSONS VECTOR BOSONS
				SCALAR BOSONS