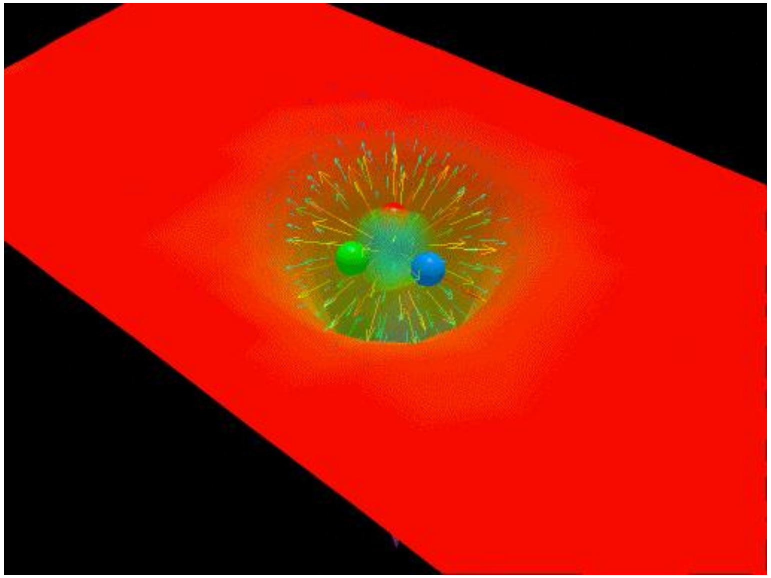
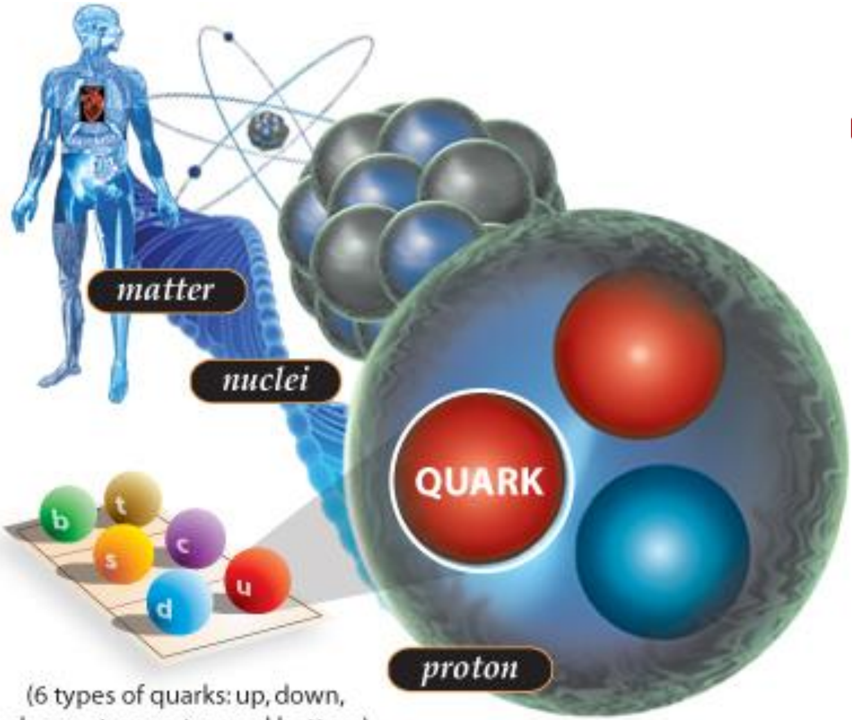


Nuclear Physics

Exploring the Heart of Matter

David Lawrence
Jefferson Lab Newport News VA, USA

With slides provided by Latifa Elouadrhiri



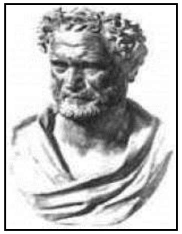
(6 types of quarks: up, down, charm, strange, top and bottom)

Part I
Introduction to the structure of matter

The Greek Revolution

Atomic theory first originated with Greek philosophers about 2500 years ago. This basic theory remained unchanged until the 19th century when it first became possible to test the theory with more sophisticated experiments.

<u>The atomic theory</u> of matter was first proposed by **Leucippus,** a Greek philosopher who lived at around 400BC. He called the indivisible particles, that matter is made of, atoms (from the Greek word atomos, meaning "indivisible").



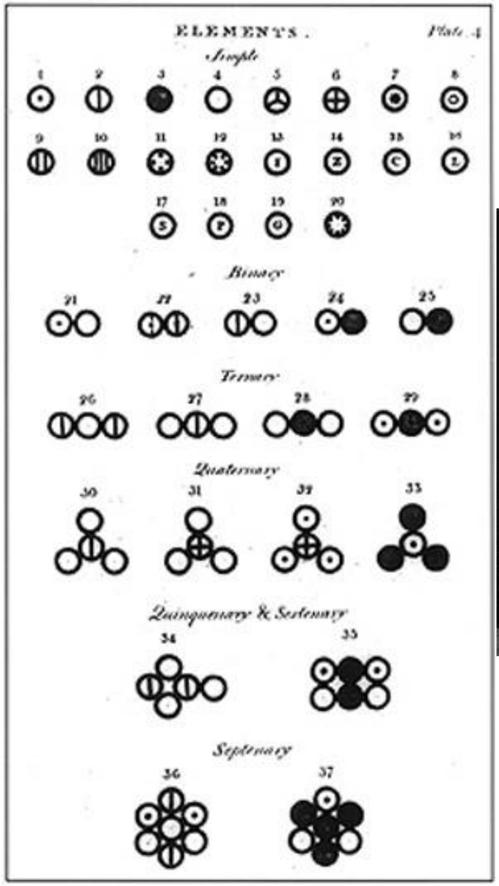
Leucippus's <u>atomic theory</u> was further developed by his disciple, **Democritus.**

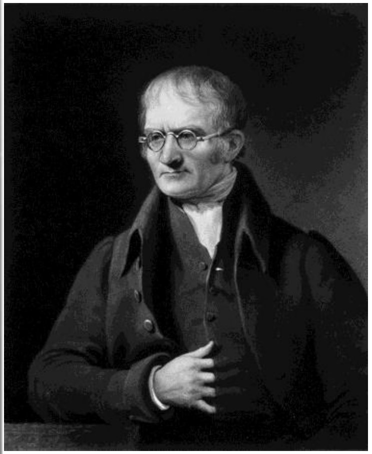
Aristotle and **Plato** favored the ***<u>earth,</u>*** ***<u>fire</u>***, ***<u>air</u>*** *and* ***<u>water</u>*** approach to the nature of matter.

The Atom

The birth of atomic theory was revived in the nineteenth century, with the birth of modern science.

In 1803 **J. Dalton** postulated the existence of **<u>the chemical elements (atoms!)</u>** To explain the variety of compounds known



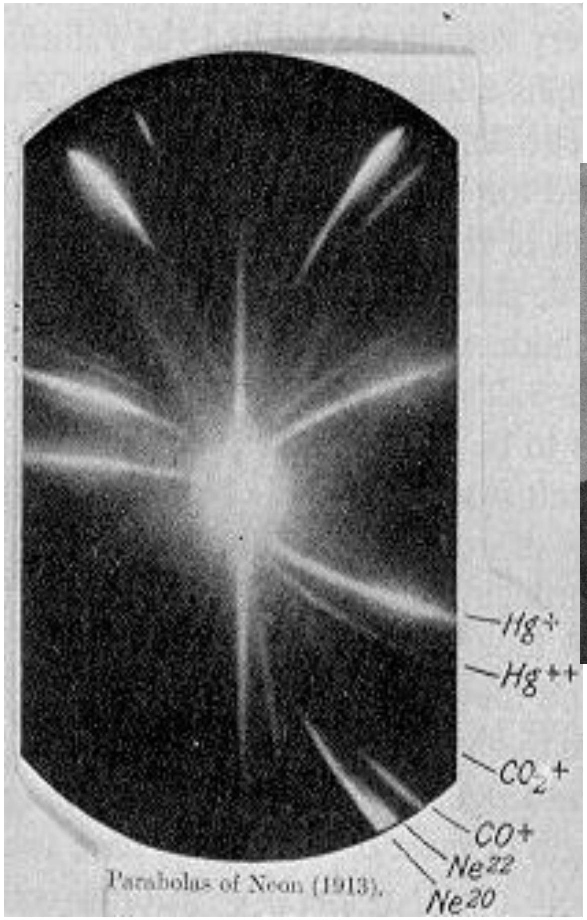


The Atom

Our current knowledge of the structure of the atom is the result of the work of many scientists and their discoveries

In 1803 **J. Dalton** postulated the existence of **<u>the chemical elements (atoms!)</u>** To explain the variety of compounds known

In 1897, **JJ. Thomson**, with his studies on cathode rays and the discovery of the **<u>electron</u>**, destroyed the concept of the atom as an indivisible particle



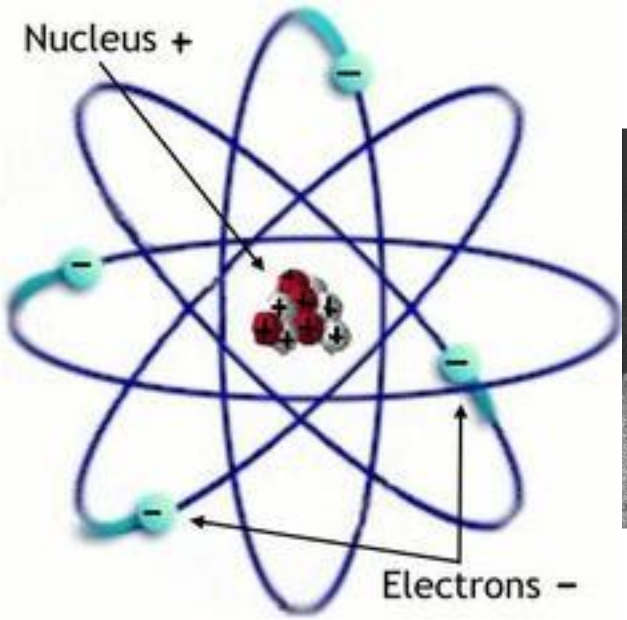
The Atom

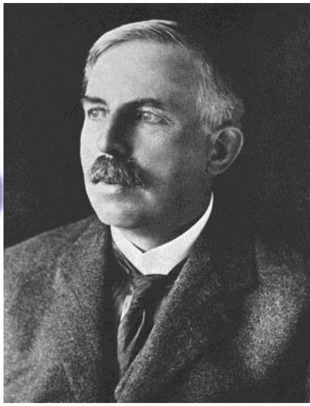
Our current knowledge of the structure of the atom is the result of the work of many scientists and their discoveries

In 1803 **J. Dalton** postulated the existence of **the chemical elements (atoms!)** To explain the variety of compounds known

In 1897, **JJ. Thomson**, with his studies on cathode rays and the discovery of the **electron**, destroyed the concept of the atom as an indivisible particle

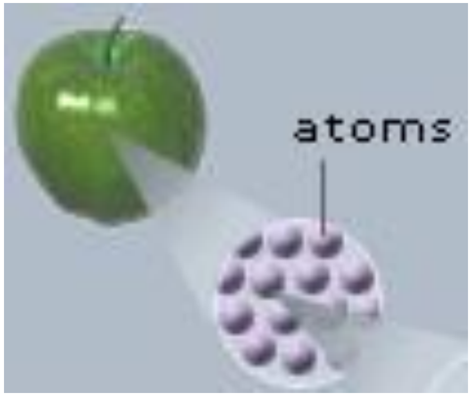
In 1911, **E. Rutherford's** experiment and the development of **quantum mechanics** led to the **modern atomic models**





We and all things around us are made of atoms

Human Hair
~ 50 μm = 50 10^{-6} m
= 0.000050 m

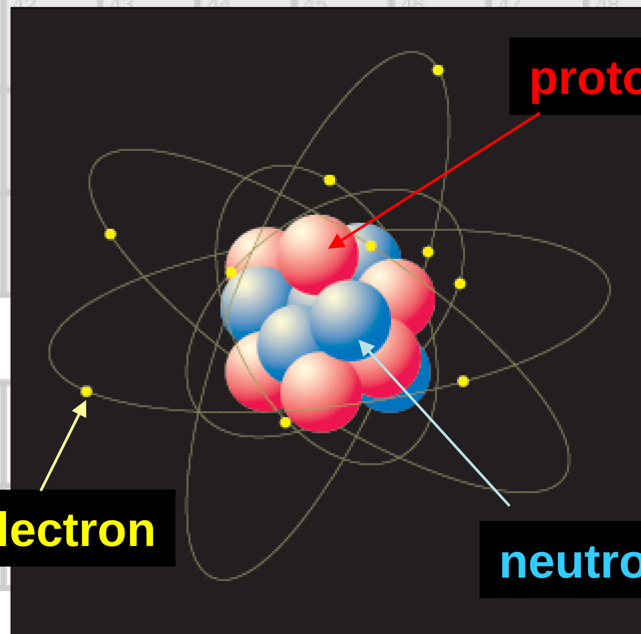


Atom ~ 10^{-10} m
= 0.0000000001 m

Atoms

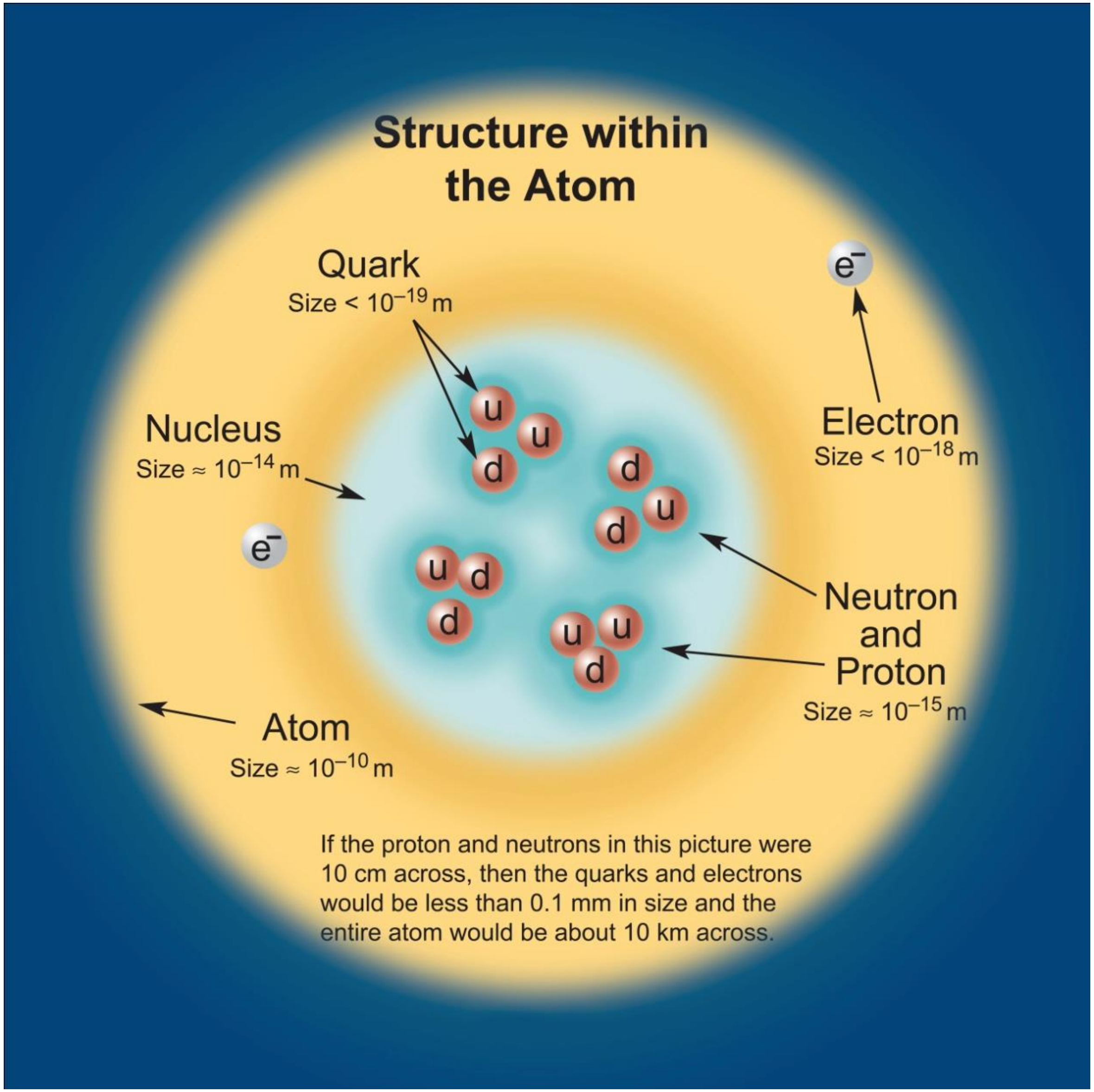
Atoms are all similarly made of:
- **protons and neutrons in the nucleus**
- **electrons orbiting around**

The electron was the first elementary particle to be discovered (JJ Thomson 1897)



Protons, neutrons are made up of quarks

From the Atom to the quark



Atoms and sub-atomic particles are much smaller than visible light wave-length
Therefore, we cannot really "see" them (all graphics are artist's impressions)
To learn about the sub-atomic structure we need particle accelerators

Quarks

- Quarks are elementary particles, ie, indivisible, and there are 6 different types, called flavors
- Have electric charge and a new type of call charge **color**(***R***, ***G***, ***B***)

6 flavors:
up, down, strange, charm, bottom, top

Electric charge
± 1/3, ± 2/3

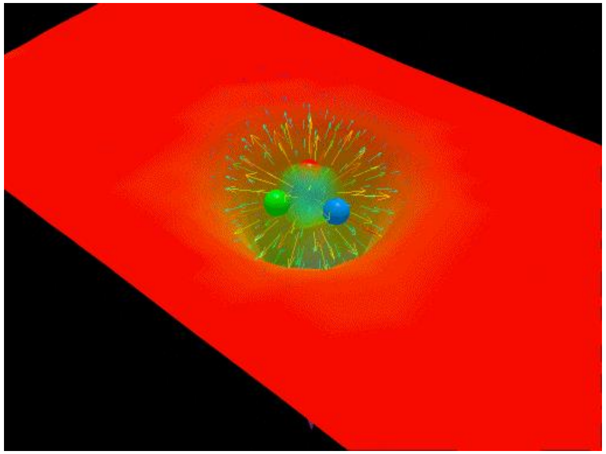
Charge color(***R***, ***G***, ***B***)

Quarks

- Quarks are elementary particles, ie, indivisible, and there are 6 different types, called flavors

- Have electric charge and a new type of call charge **color**(***R*, *G*, *B***)

- The quarks interact via the **strong nuclear force**, which manifests itself through the exchange of force carriers called gluons



Hadrons

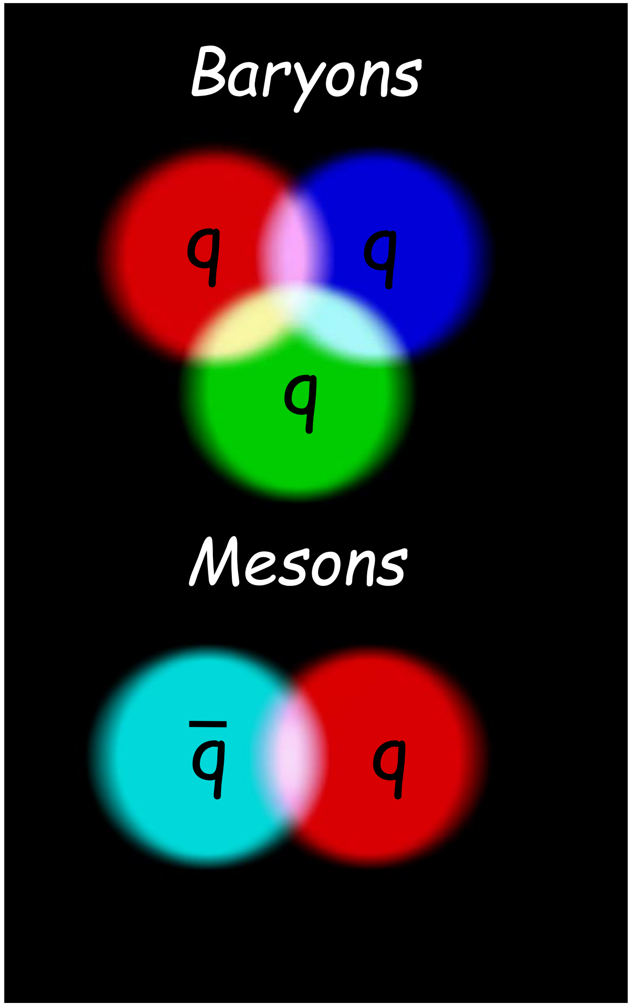
- Quarks are elementary particles, ie, indivisible, and there are 6 different types, called flavors

- Have electric charge and a new type of call charge **color**(***R***, ***G***, ***B***)

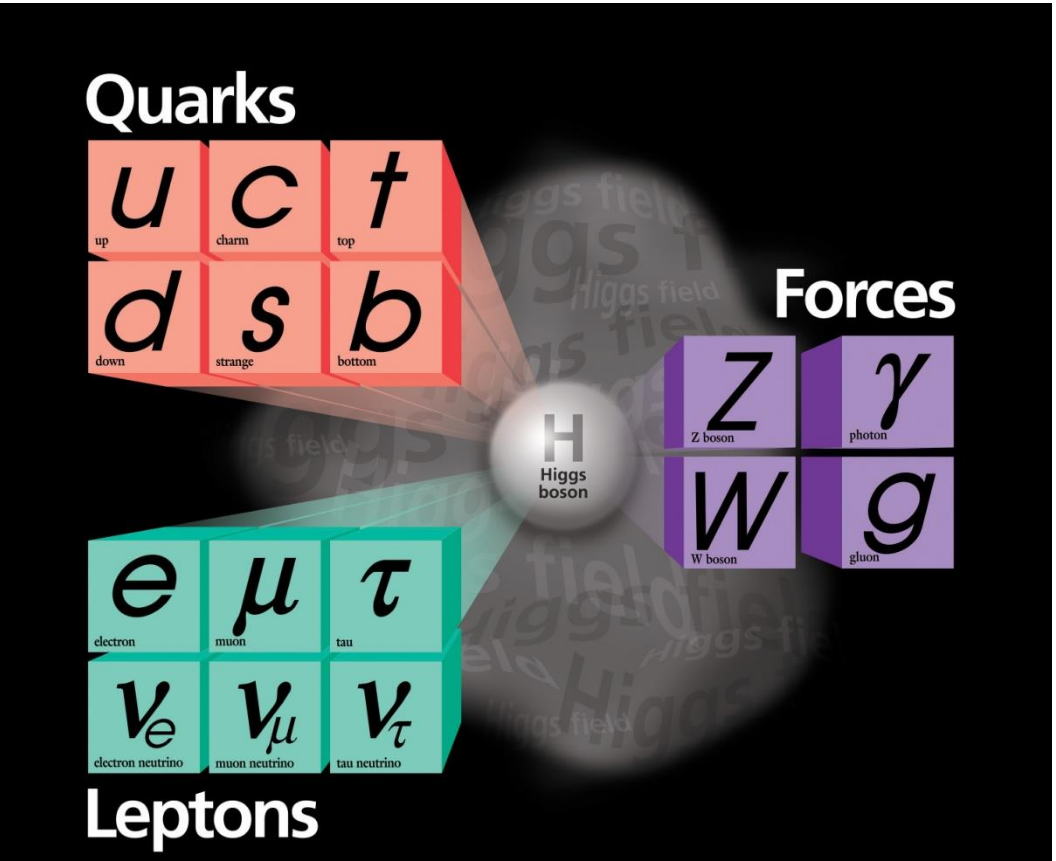
- The quarks interact via the **strong nuclear force**, which manifests itself through the exchange of force carriers called gluons

- A Free quark has never been observed. (A property called “confinement” that is still a bit mysterious)

- Quarks combine to form objects colorless "white" object called **hadrons: baryons** are known configurations (3q) and **mesons** (qq)



The Standard Model



H: the Higgs Boson

Framework which includes:

Matter
- 6 quarks
- 6 leptons

Grouped in three generations

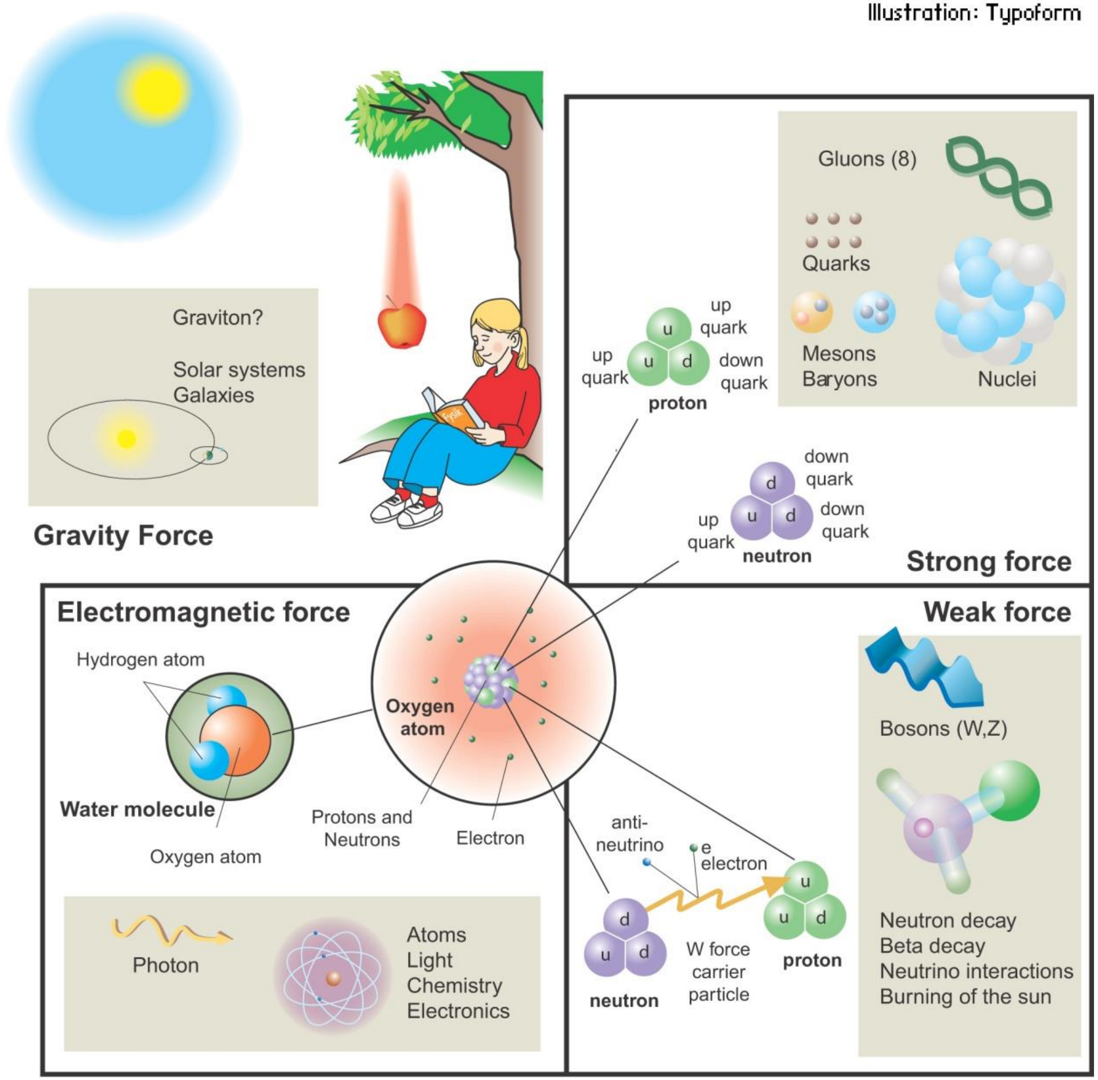
Forces
- Electroweak:
  - γ (photon)
  - Z^0, $W^\pm$
- Strong
  - g (gluon)

Not gravity! No quantum field theory of gravity yet..

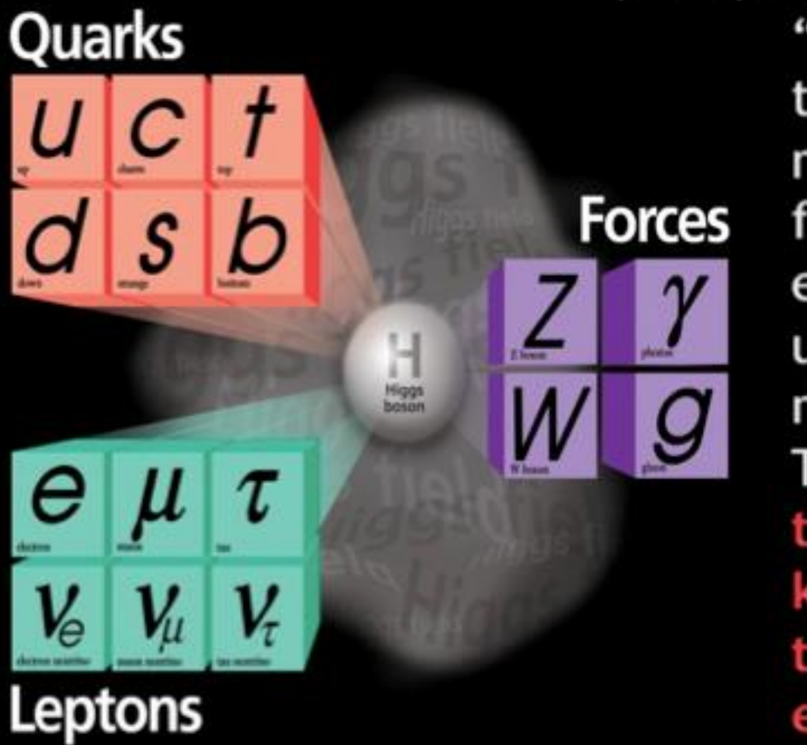
Simple and comprehensive theory that explains hundreds of particles and complex interactions

The Four Fundamental Forces

Illustration: Typoform



The Standard Model and our world

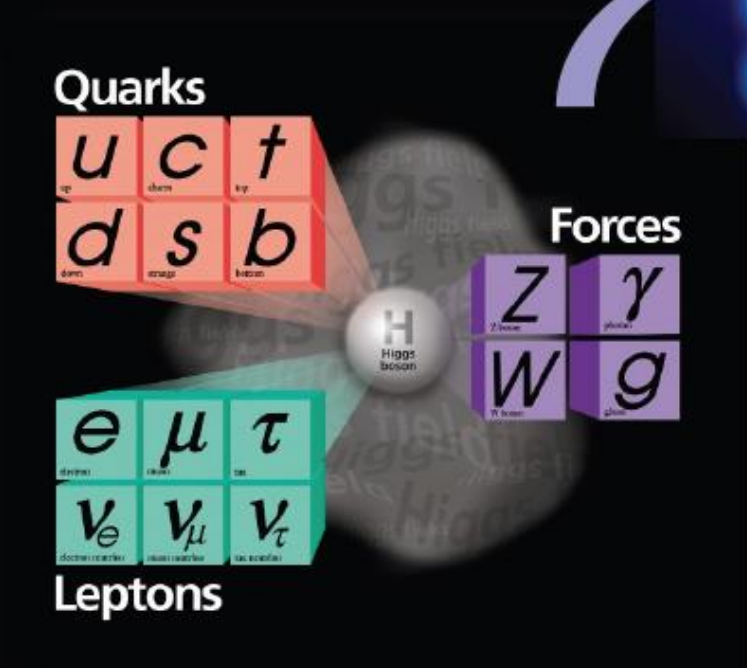


From the D. Gross Nobel Lecture (2004):

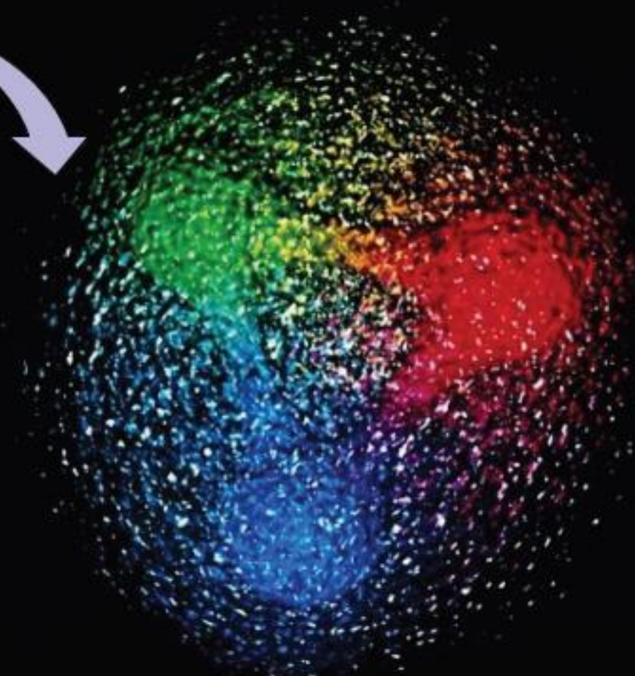
"It is sometimes claimed that the origin of mass is the Higgs mechanism that is responsible for the breaking of the electroweak symmetry that unbroken would forbid quark masses.
This is incorrect. Most, 99%, of the proton mass is due to the kinetic and potential energy of the massless gluons and the essentially massless quarks, confined within the proton."

The Standard Model & the QCD

Elementary Particles



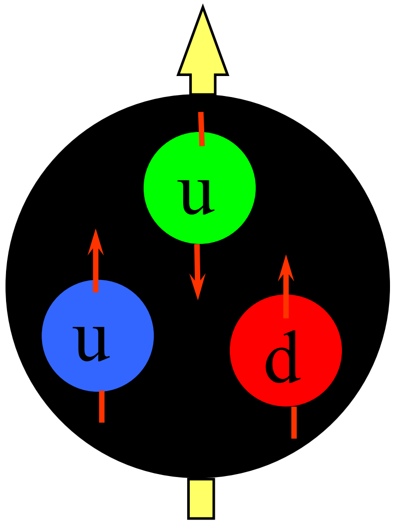
Nucleon



Proton Mass $\gg$ M(up) + M(up) + M(down) ~ 10 MeV

Proton Spin : Only 25% of the proton spin is carried by the quarks

Constituent Quark model



The proton is built from three quarks of spin s = 1/2
and having masses m_q ~ 300 MeV*

**actual u,d quark masses are ~2-5MeV*

M. Gell-Mann, 1964
G. Zweig, 1964

- Proton mass: $m_p \approx 3m_q$
- Proton spin: $\vec{S} = \frac{\vec{1}}{2} \oplus \frac{\vec{1}}{2} \oplus \frac{\vec{1}}{2}$

Solely built from the quark spins!

Tremendously successful model in description of

- Hadron mass spectra

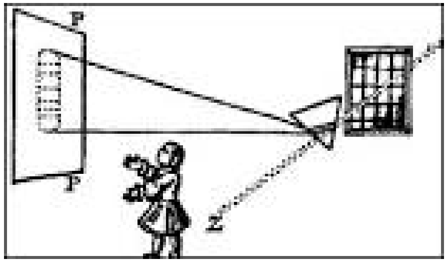
Spectrum of the hydrogen atom

- Much of what we know about the structure of the hydrogen atom we know from the excitation spectrum created by its constituents: proton, electron, and the electromagnetic field generating sharp energy levels.

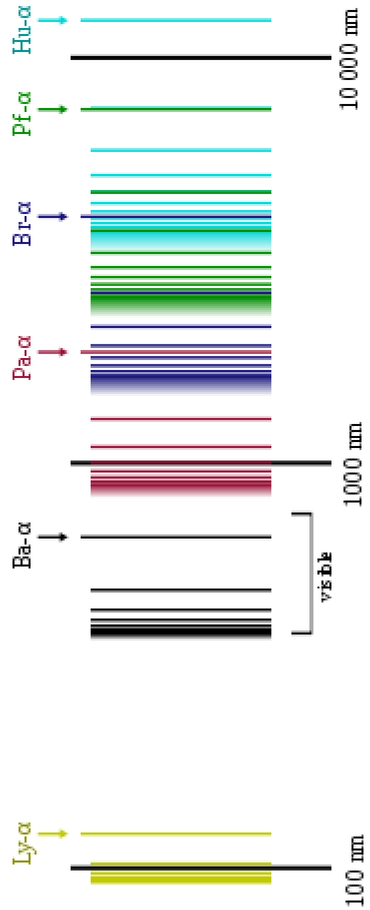
- Much of the structure of the proton is revealed by the excitation spectrum of its constituents.

- The proton constituents are strongly interacting particles (quarks, gluons), giving rise to very broad energy levels that are difficult to isolate.

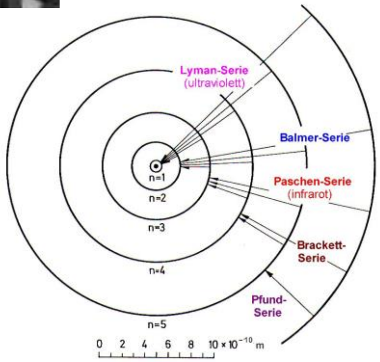
I. Newton, 1666



Spectral series of hydrogen, today



N. Bohr 1913



Nuclear Shell Model

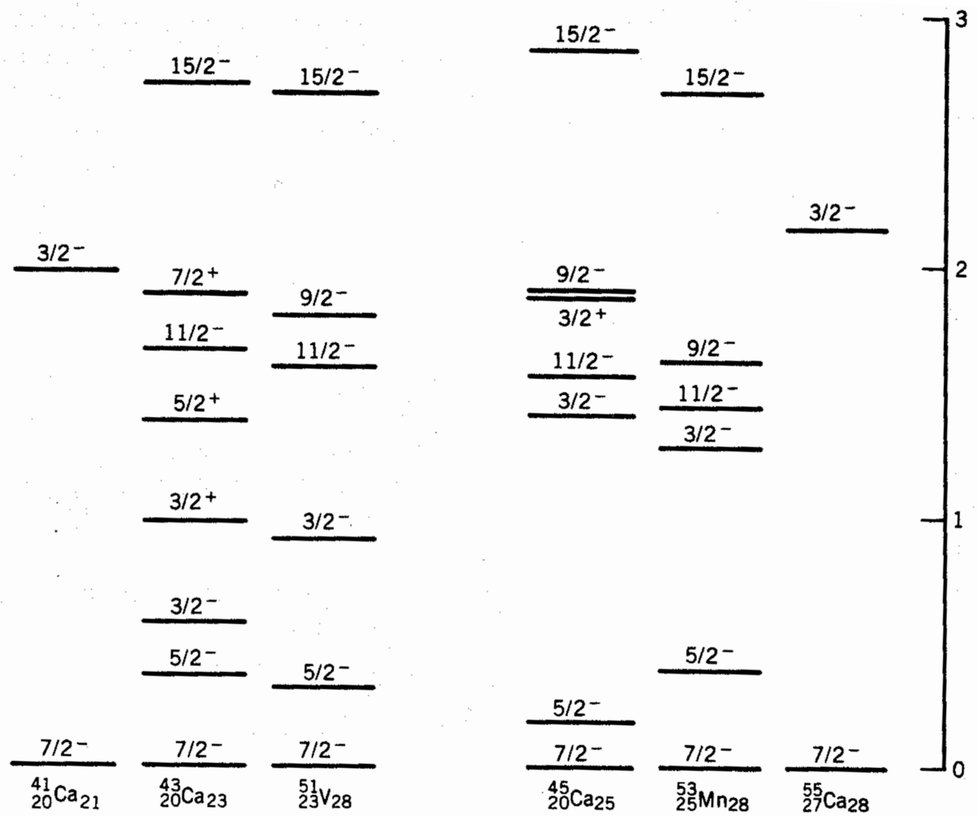
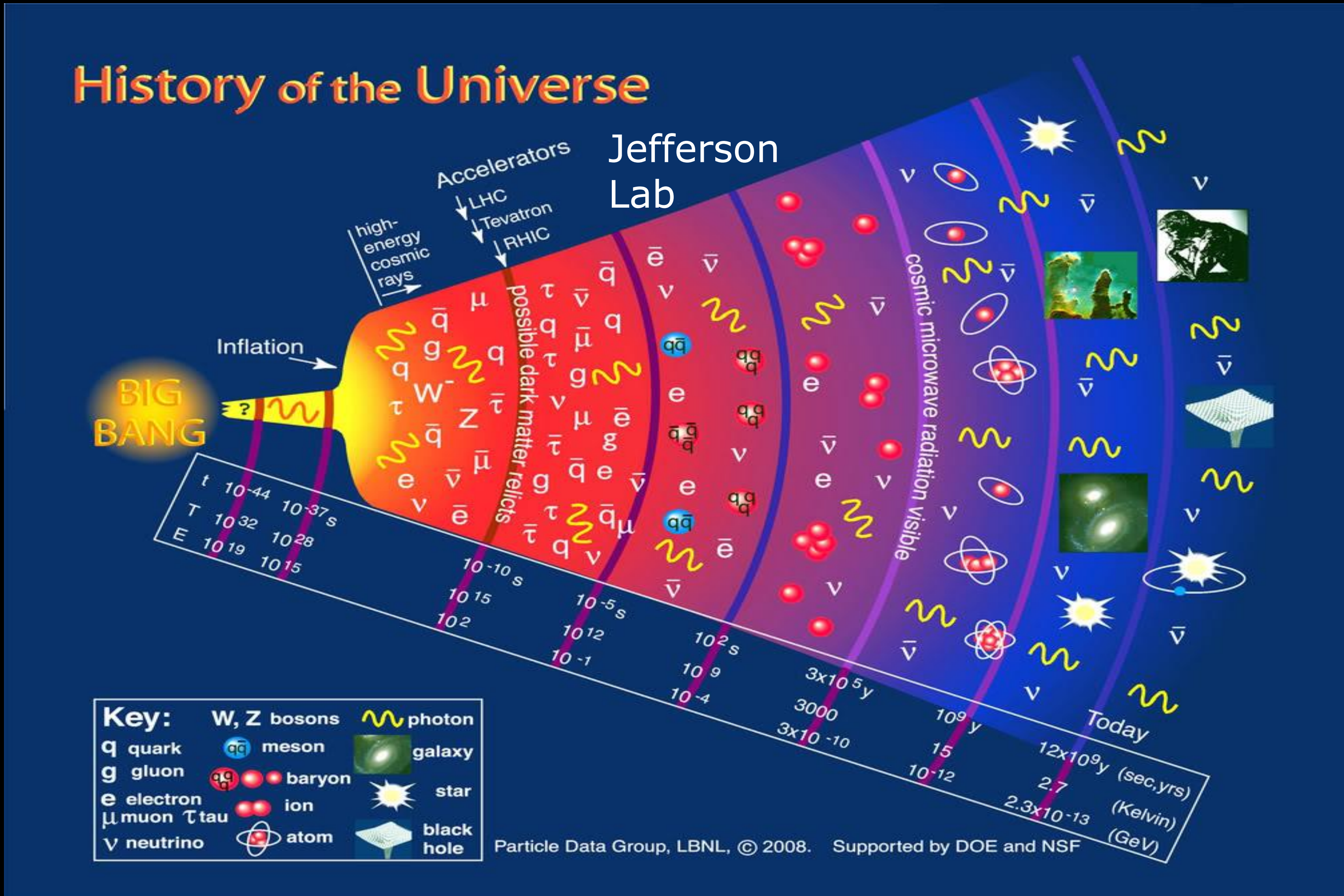


Figure 5.25 Excited states of some nuclei with valence particles in the $f_{7/2}$ shell. All known levels below about 2 MeV are shown, and in addition the $\frac{15}{2}^-$ state is included.

From "Introductory Nuclear Physics", Kenneth S. Krane, 1988 Wiley Publishing

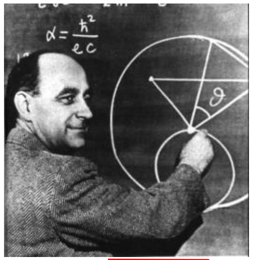
The Nuclear Shell model can describe excitation energies of nuclei where the protons and neutrons act in a similar role as the electrons in the Atomic Shell model.

This pattern of excitation energies is determined by the physical forces binding the nucleons in the nucleus.


History of the Universe
Jefferson Lab
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
ion
star
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Backups

First baryon resonance and beyond

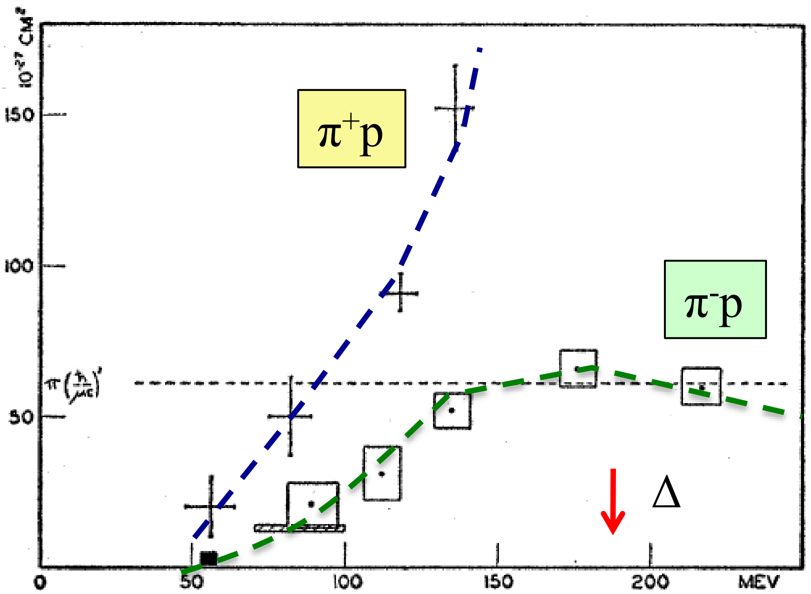


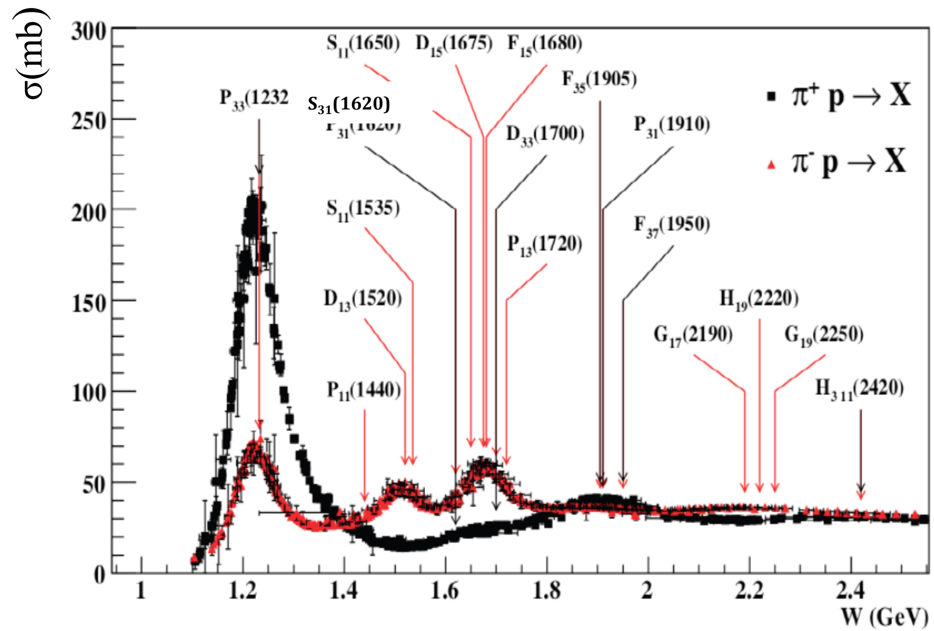
E. Fermi , 1952

Total Cross Sections of Positive Pions in Hydrogen*

H. L. Anderson, E. Fermi, E. A. Long,† and D. E. Nagle
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 21, 1952)





Many states discovered in pion-nucleon elastic scattering πN-->πN.

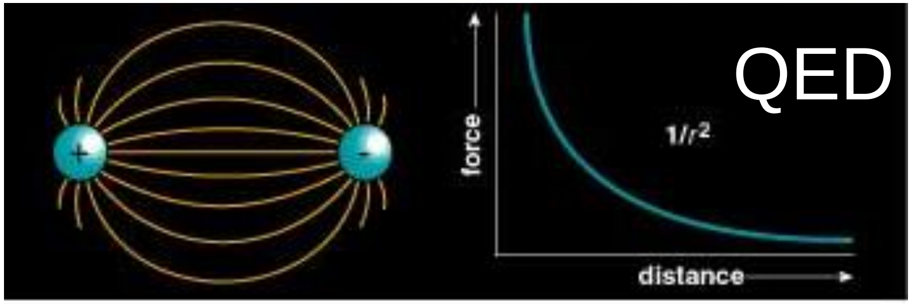
Many states expected from symmetric CQM were not found – have they escaped detection because they do not couple to πN?

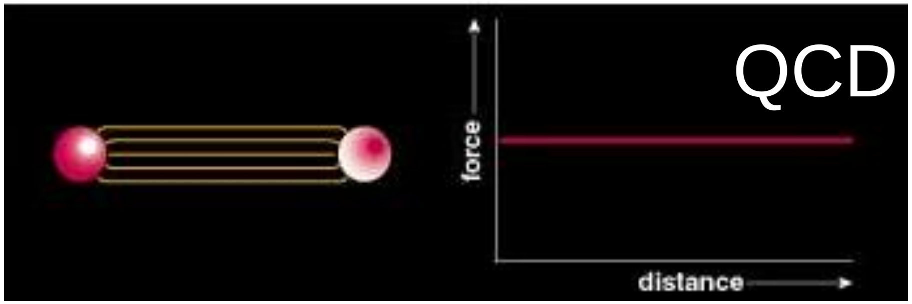
Quantum ChromoDynamics (QCD)

The interaction is governed by massless spin 1 objects called "gluons".

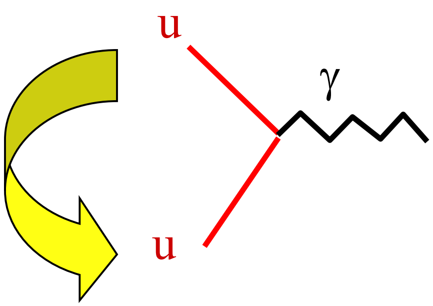
- Gluons couple only to objects that have "color": quarks and gluons
- There are three different charges ("colors"): red, green, blue.
- There are eight different gluons. gluon exchange can change the color of a quark but not its flavor.

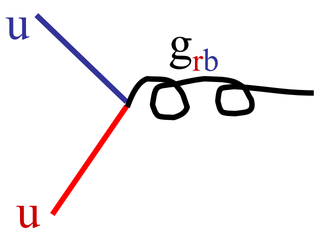
e.g. a red u-quark can become a blue u-quark via gluon exchange.

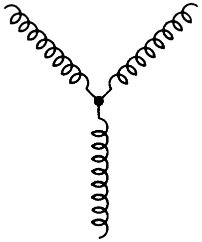


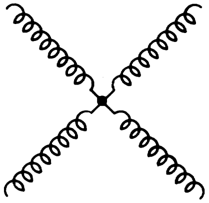


The gluons of QCD carry color charge and interact strongly (in contrast to the photons of QED).









Note: in QED there is only one charge (electric).

Asymptotic Freedom of QCD

The Nobel Prize in Physics 2004

Gross, Politzer, Wilczek: "for the discovery of asymptotic freedom in the theory of the strong interaction"


David J. Gross

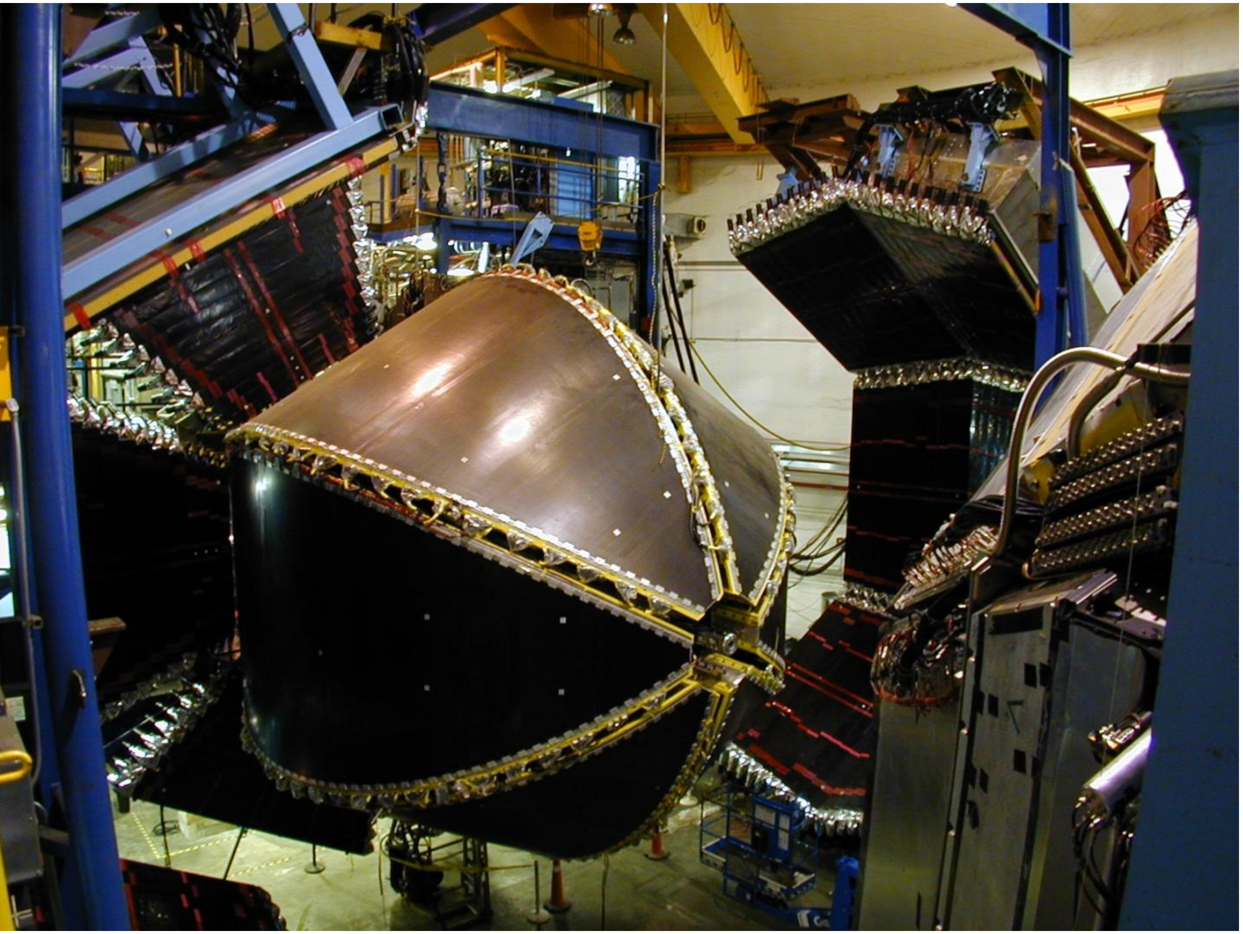

H. David Politzer


Frank Wilczek

Asymptotic freedom: As the distance between two quarks asymptotically approaches zero, the force becomes arbitrarily weak and the quarks appear to be free. Similarly quarks at very high energies appear to exist as free particles,

A 'colourful' discovery in the world of quarks

CEBAF Large Acceptance Detector (CLAS)



This unique particle detector was constructed over Seven-year period.
The spherical shape allows particles to be detected in many directions at once creating an incredible one terabyte of data a day to be analyzed.

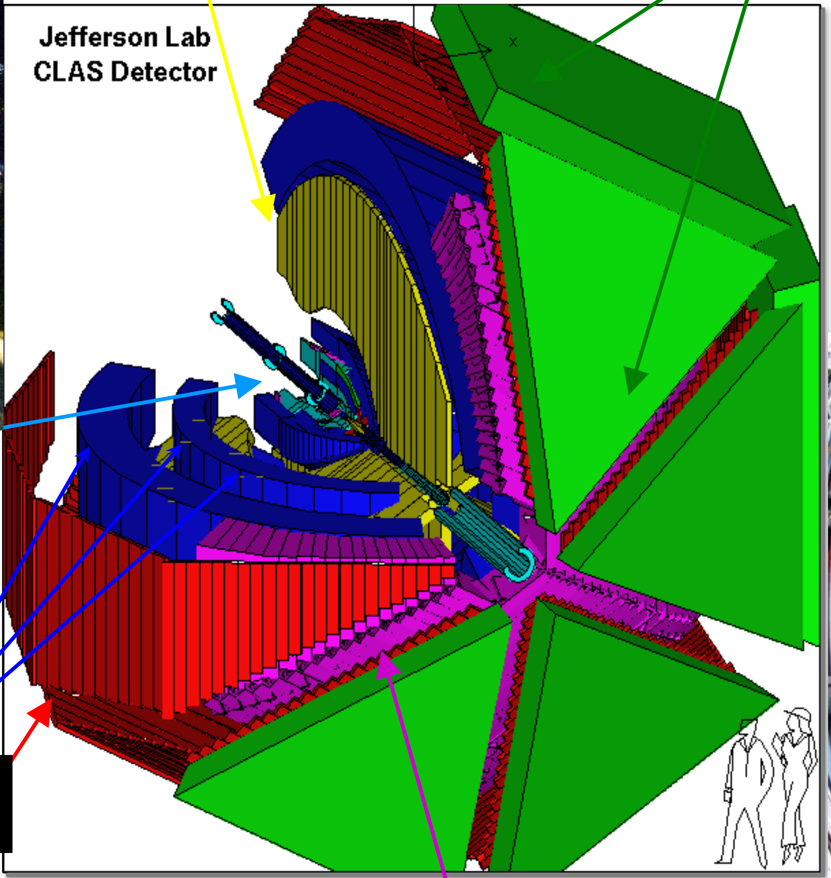
Scientist from all around the world used this detector to conduct experiments to better understand the interactions between quarks and gluons, that hold quarks together to form protons and neutrons

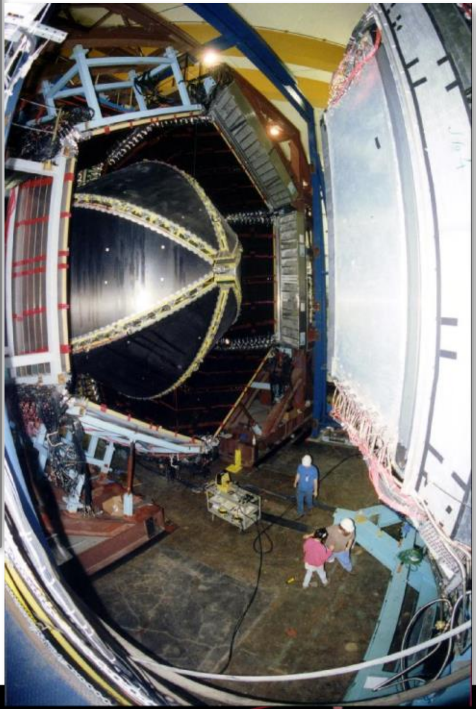
CEBAF Large Acceptance Spectrometer

Torodial Magnet

6 Superconductin coils

Electromagnetic Calorimeter
Lead/Scintillator, 1296 channels





Target + □
start counter
and mini-torus

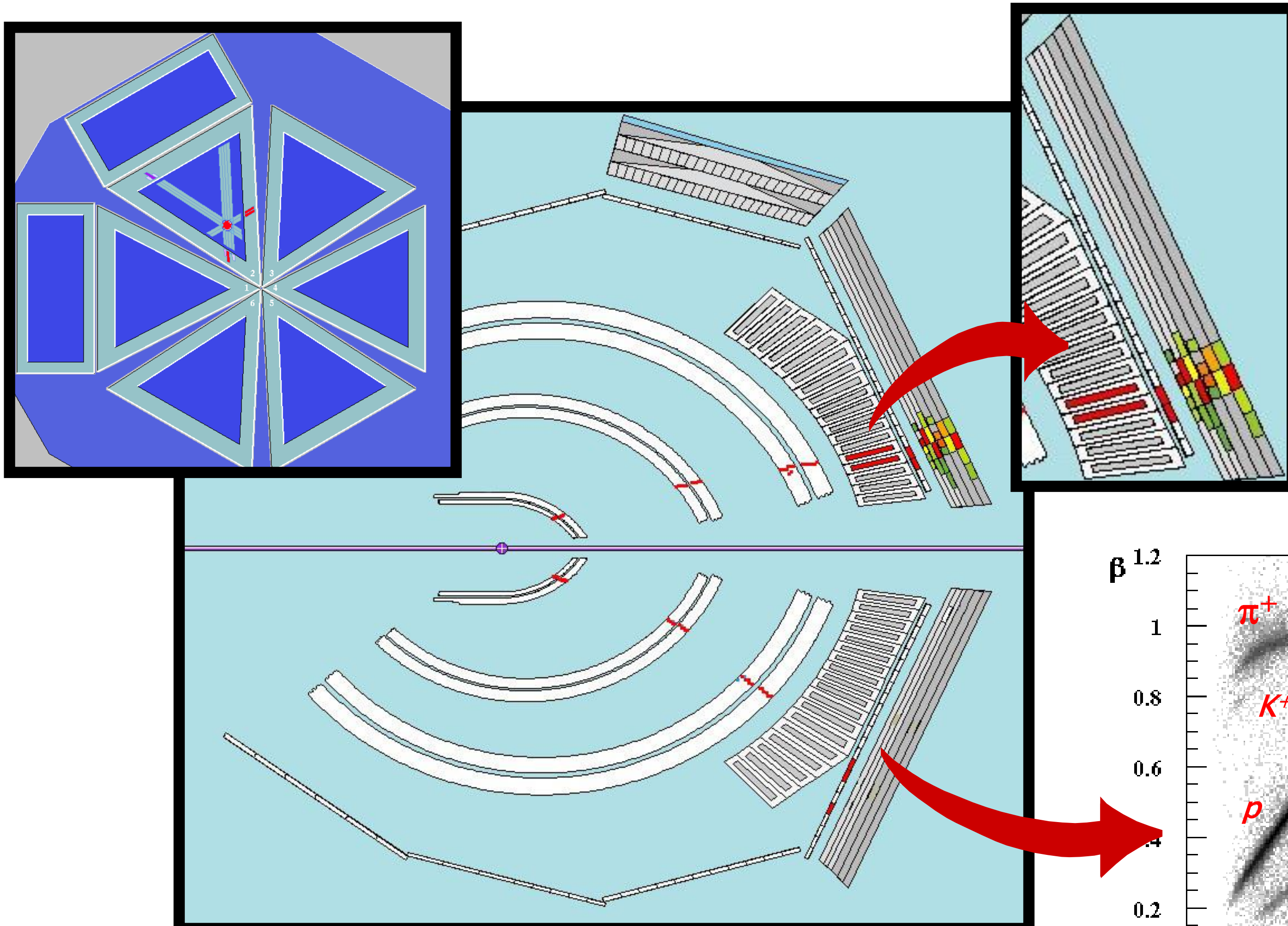
Drift Chambers

35,000 cells

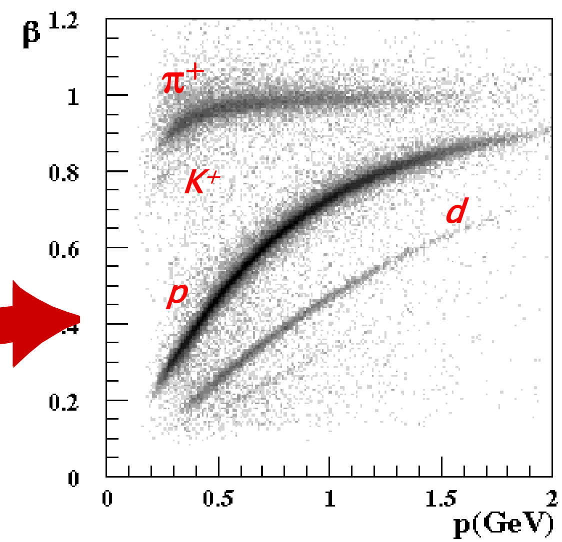
Time of Flight
Plastic scintillator 684 channels

Cherenkov Counter e/□
separation, 256 PMTs

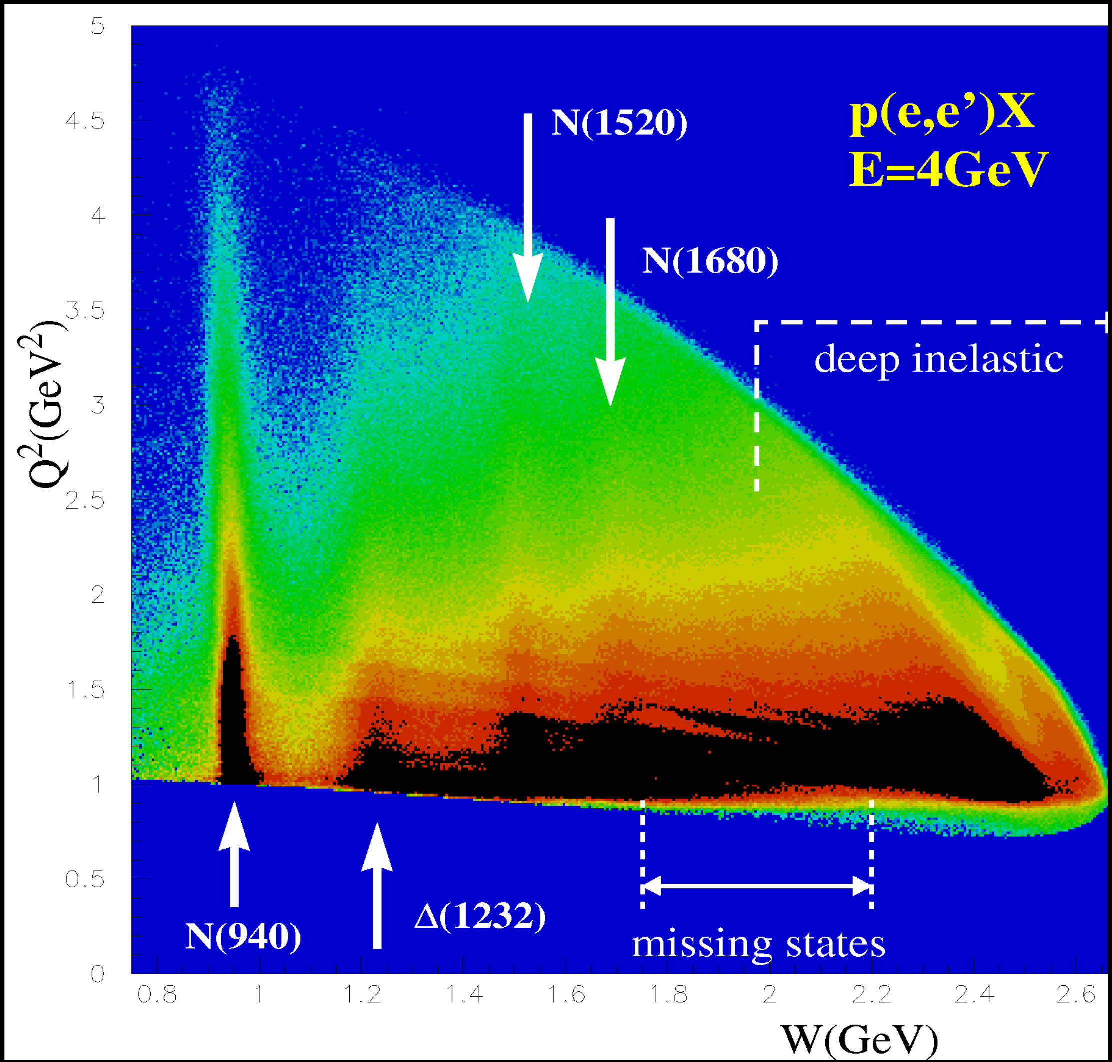
Physics with CLAS



The Particle are identified speed

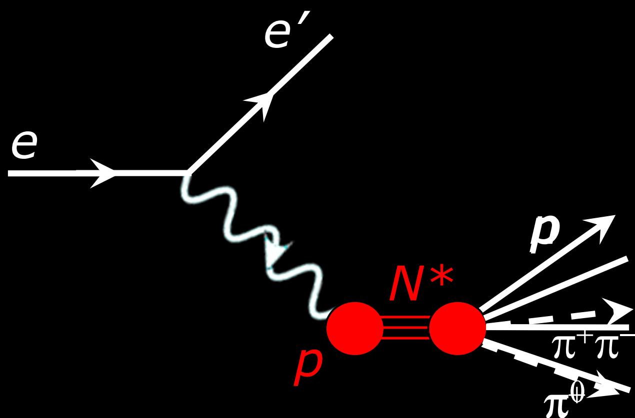


Nucleon Excitation



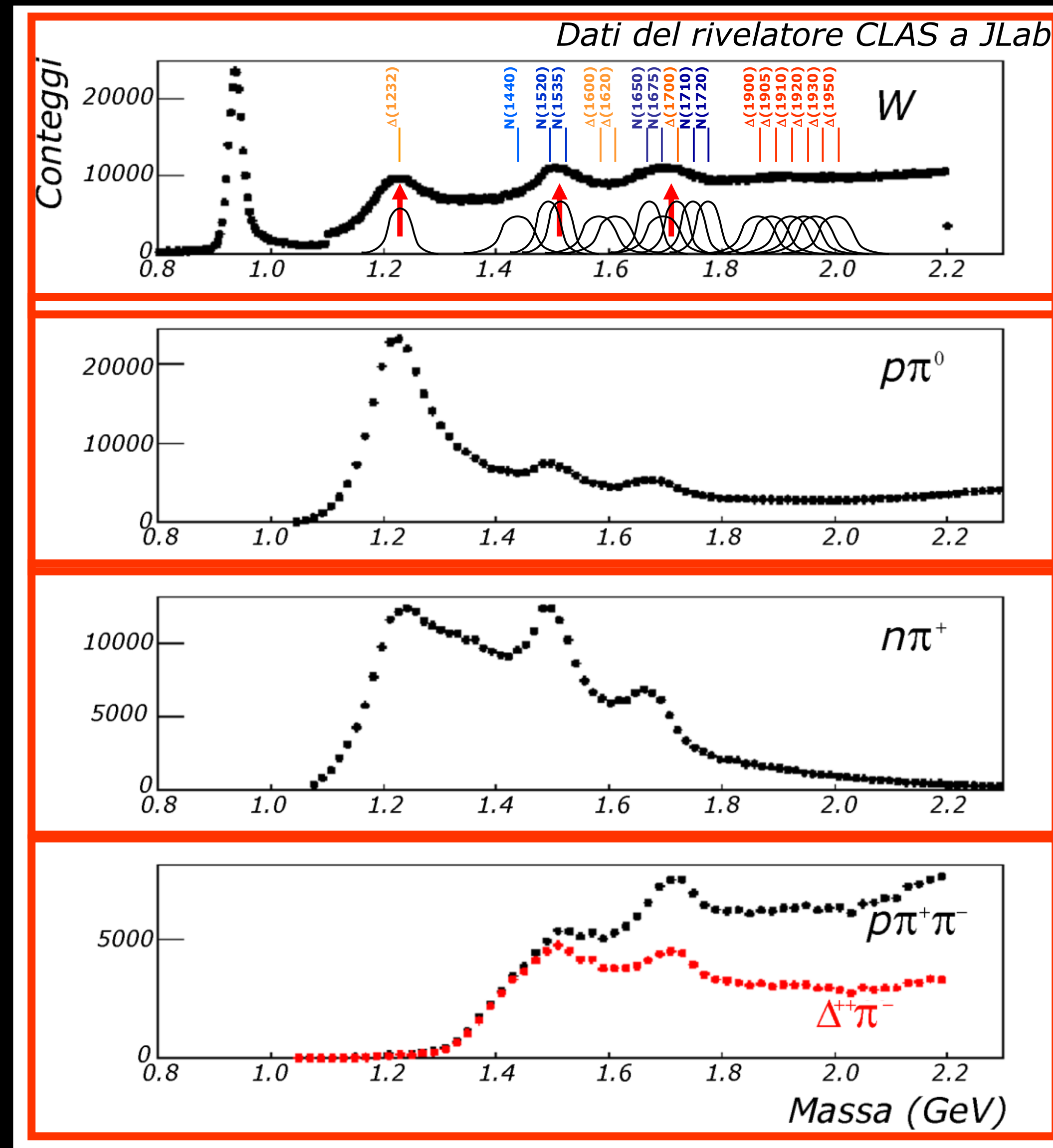
First experiments with CLAS

Nucleon excited states with the CLAS Detector



Nucleon excited states mass spectrum. The resonance width depend on the resonance life time

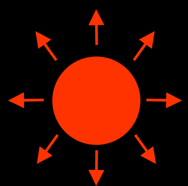
The measurement of the final states allows the separation of different resonances

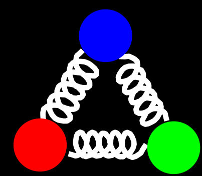


Roper resonance example nucleon excitation study with CLAS

The Roper is the second excited state of the proton, it is still one of the most mysterious

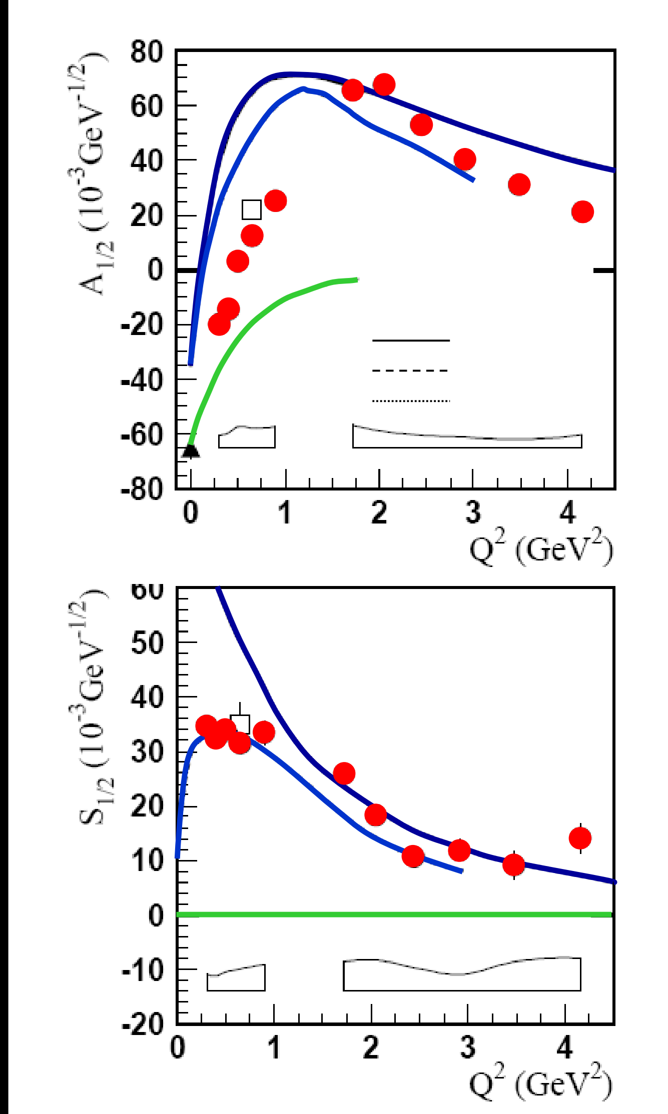
- is it due to the radial excitation of the nucleon?
- is it a hybrid state 3QG?





The data from CLAS at JLab have allowed for the **<u>first time</u>** to study this state with great precision (*text Book results*)

- data are consistent with the predictions of the quark models for the radial excitation
- exclude the hypothesis that the Roper is a hybrid state
- demonstrating the sensitivity of the data to the microscopic nuclear structure



I. Aznauryan et al., Phys.Rev.C78:045209,2008

Next generation of experiments
Nucleon tomography –
Introduction to the Generalized Parton Distributions (GPDs)

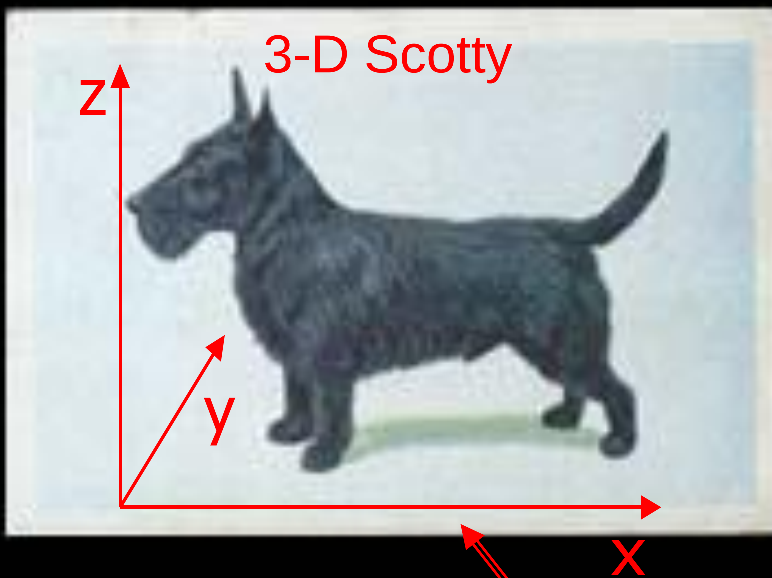
What are Generalized Parton Distributions ?

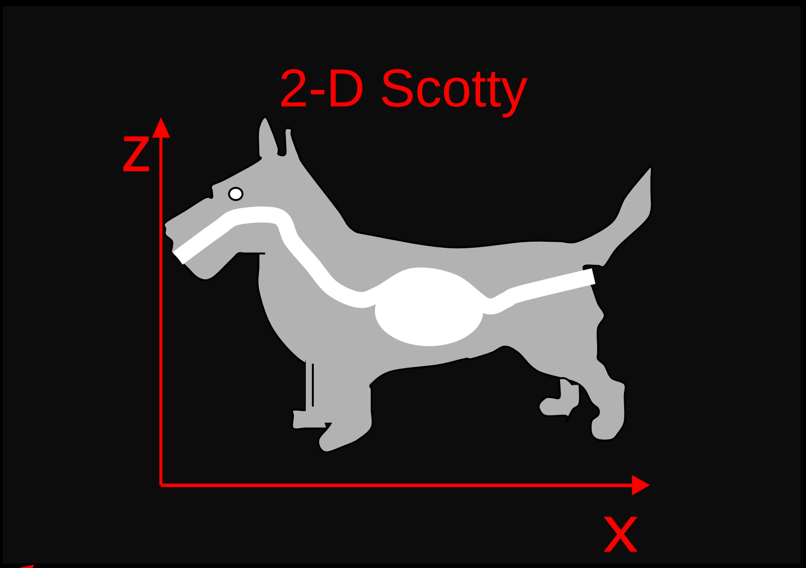
As Form Factors do, they contain information about the positions of quarks in the nucleon, like one obtains by taking a sharp picture

As ordinary Parton Distributions, they contain information on the velocity of quarks in the nucleon, like one obtains by timing track runners over a given distance

Generalized Parton Distributions combine the information content of Form Factors and ordinary Parton Distributions, both in position and velocity of quarks in the nucleon

GPDs & PDs





Deeply Virtual Exclusive Processes & GPDs

Deep Inelastic Scattering & PDs