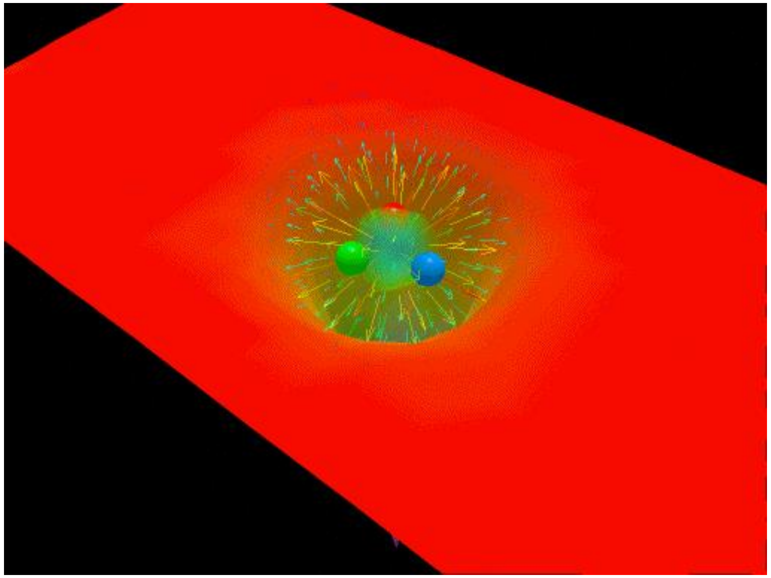
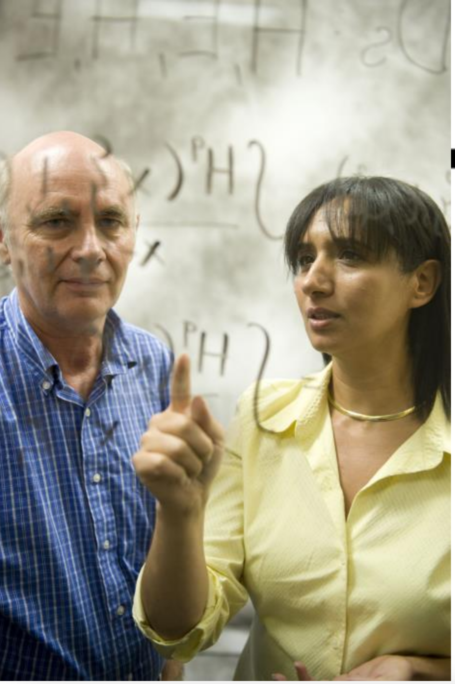


Nuclear Physics

Exploring the Heart of Matter

Latifa Elouadrhiri
Jefferson Lab Newport News VA, USA

Jefferson Lab
Thomas Jefferson National Accelerator Facility

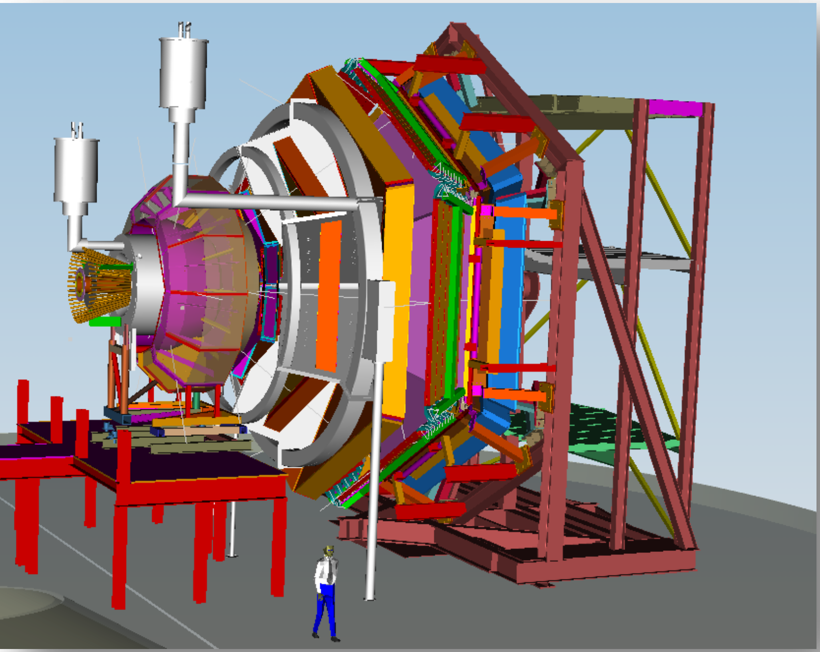


Scientist and Project Manager

Spokesperson of major science program to study the nucleon “tomography” at Jefferson Lab.

Ensure the construction of state of the art detector to conduct next generation of high precision experiments in electron scattering as part Jefferson Lab Upgrade.

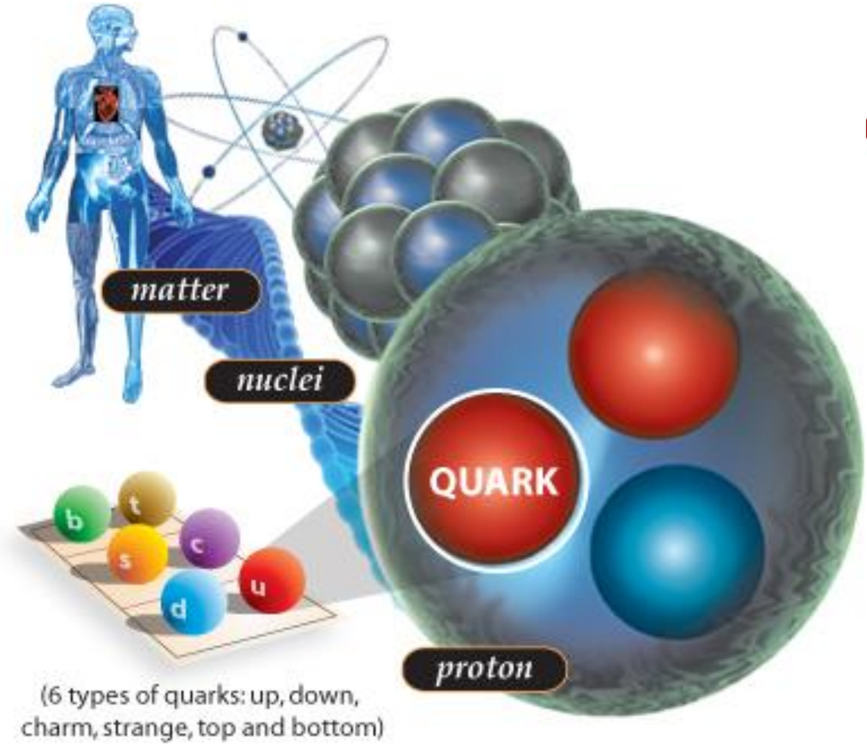
Grow world-class research and education program



The 12 GeV Upgrade is a unique opportunity for the nuclear physics community to expand its reaches into unknown scientific areas. For the first time, researchers will be able to probe the quark and gluon structure of strongly interacting systems. Jefferson Lab at 12 GeV will make profound contributions to the study of hadronic matter-the matter that makes up everything in the world.

Outline

- General Introduction to the structure of matter
- Electron scattering and Formalism
- Jefferson Lab-3D imaging of the nucleon
- The future of nuclear physics – Jefferson Lab upgrade



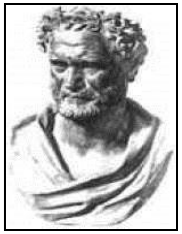
Part I
Introduction to the structure of matter

- **Ancient Atomic theory**
- **The Modern Atomic Theory**
- **Rutherford's Experiment**
- **Bohr’s Model**
- **Quantum Theory of the Atom**

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.

The atomic theory 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”).



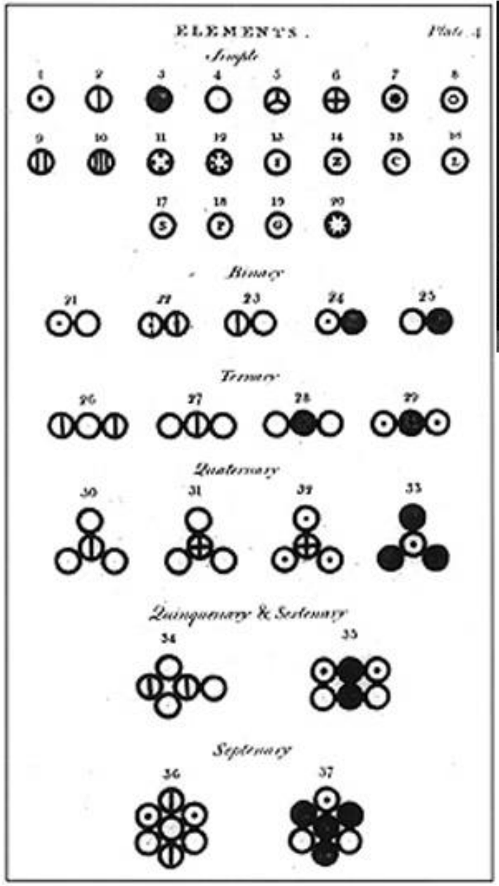
Leucippus's atomic theory was further developed by his disciple, **Democritus.**

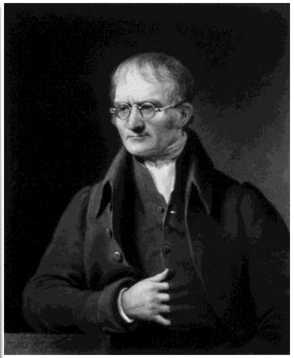
Aristotle and **Plato** favored the ***earth, fire, air*** *and* ***water*** approach to the nature of matter.

The Atom

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

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



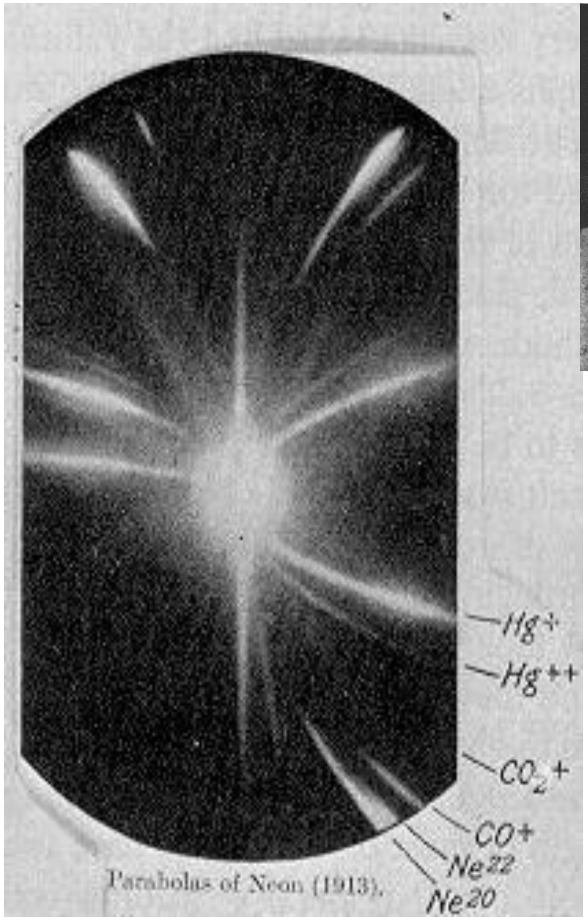


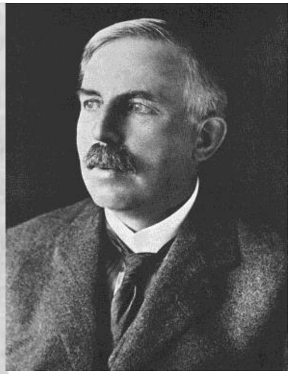
The Atom

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

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

In 1867, **JJ. Thomson**, with his studies on cathode rays and the discovery of the **electron**, jolted science into a new way of imagining the composition of matter.





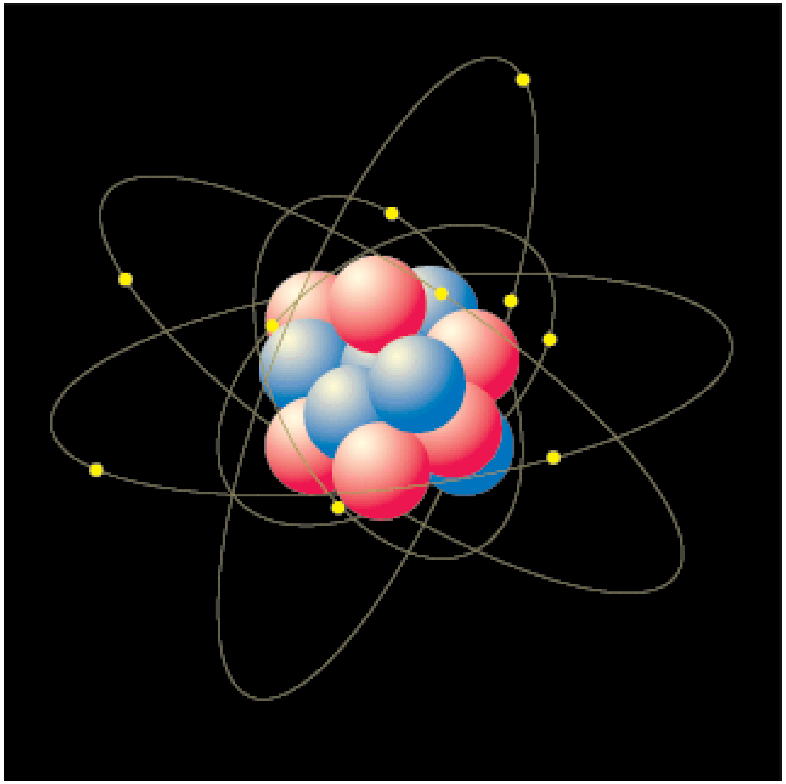
The Atom

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 1867, **JJ. Thomson**, with his studies on cathode rays and the discovery of the **electron**, destroyed the concept of the atom as an indivisible particle

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

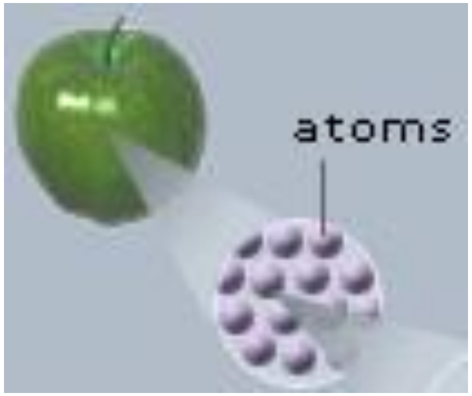


We and all things around us are made of atoms

Human Hair

~ 50 μm = 50 10^{-6} m

= 0.000050 m



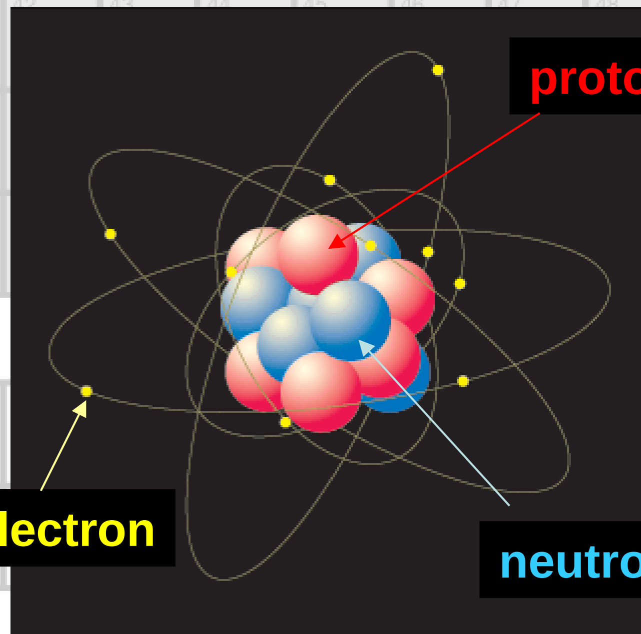
Atom ~ 10^{-10} m

= 0.0000000001 m

Atoms

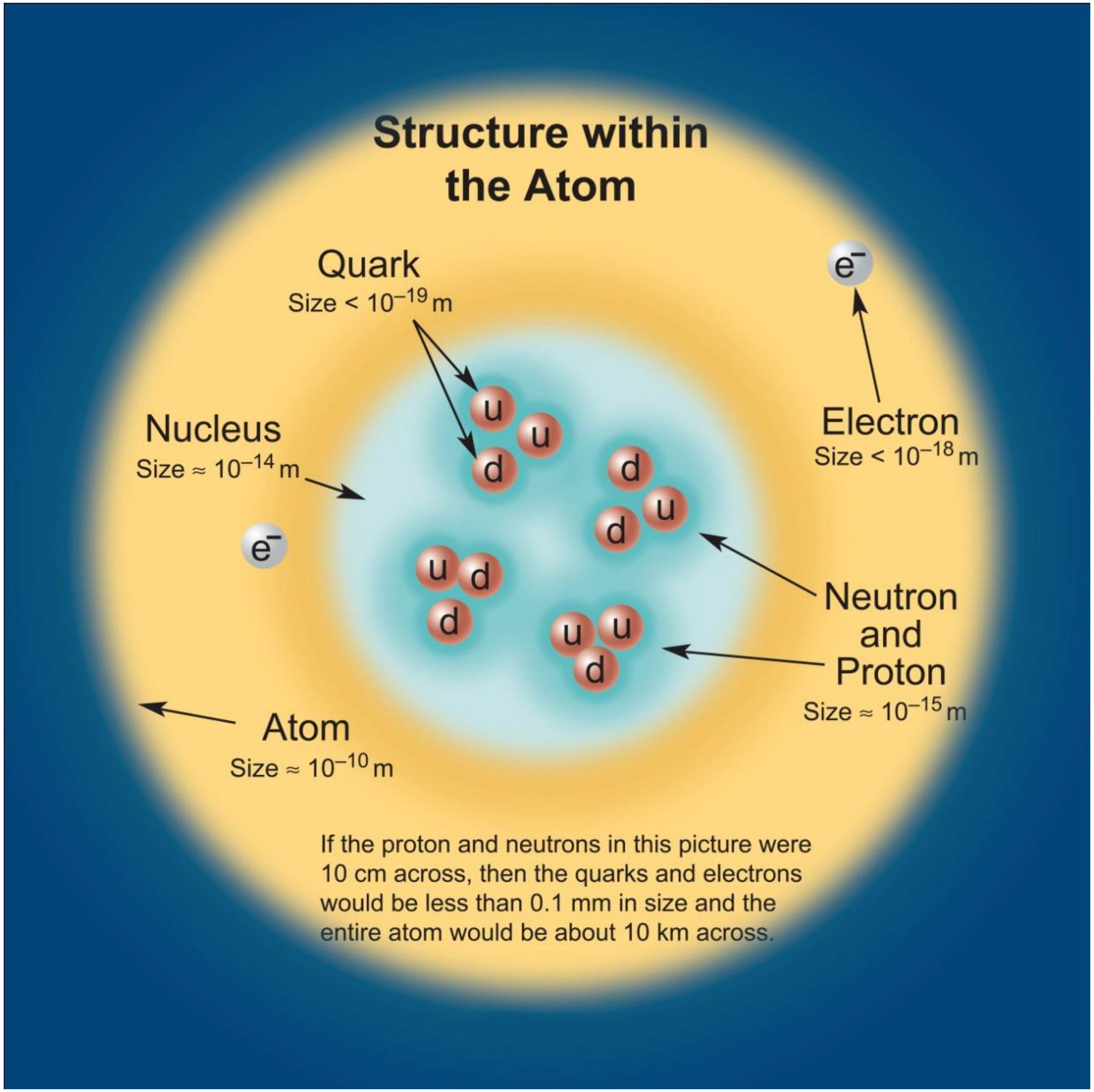
Atoms are all similarly made of:
- protons and neutrons in the nucleus
- electrons orbiting around

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



Quarks

Today we know that even protons and neutrons that make up the atomic nucleus are not indivisible particles but have an internal structure ...

…Are in fact made up of quarks

Quarks

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

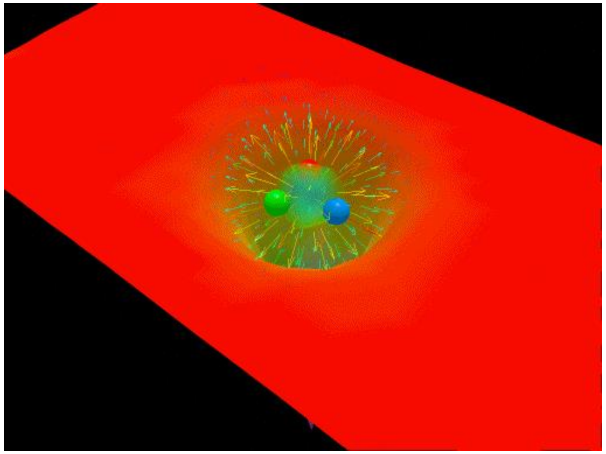
6 flavors:
up, down, strange,
charm, bottom, top

Electric charge
± 1/3, ± 2/3

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

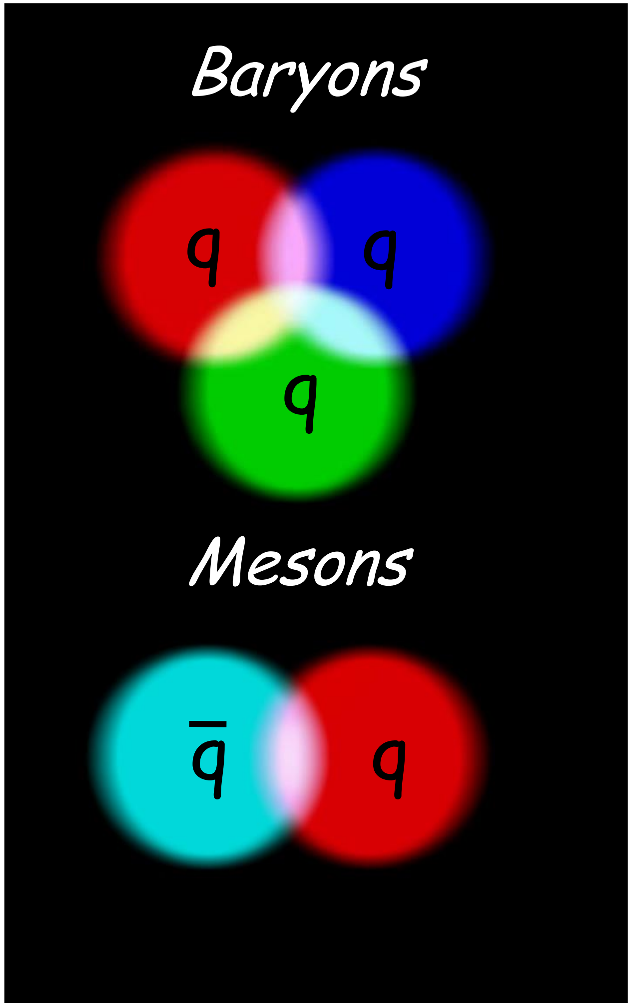
Quarks

- Quarks are elementary particles, ie, indivisible, and there are 6 different types, called flavors
- Have electric charge and also a new type of charge called 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

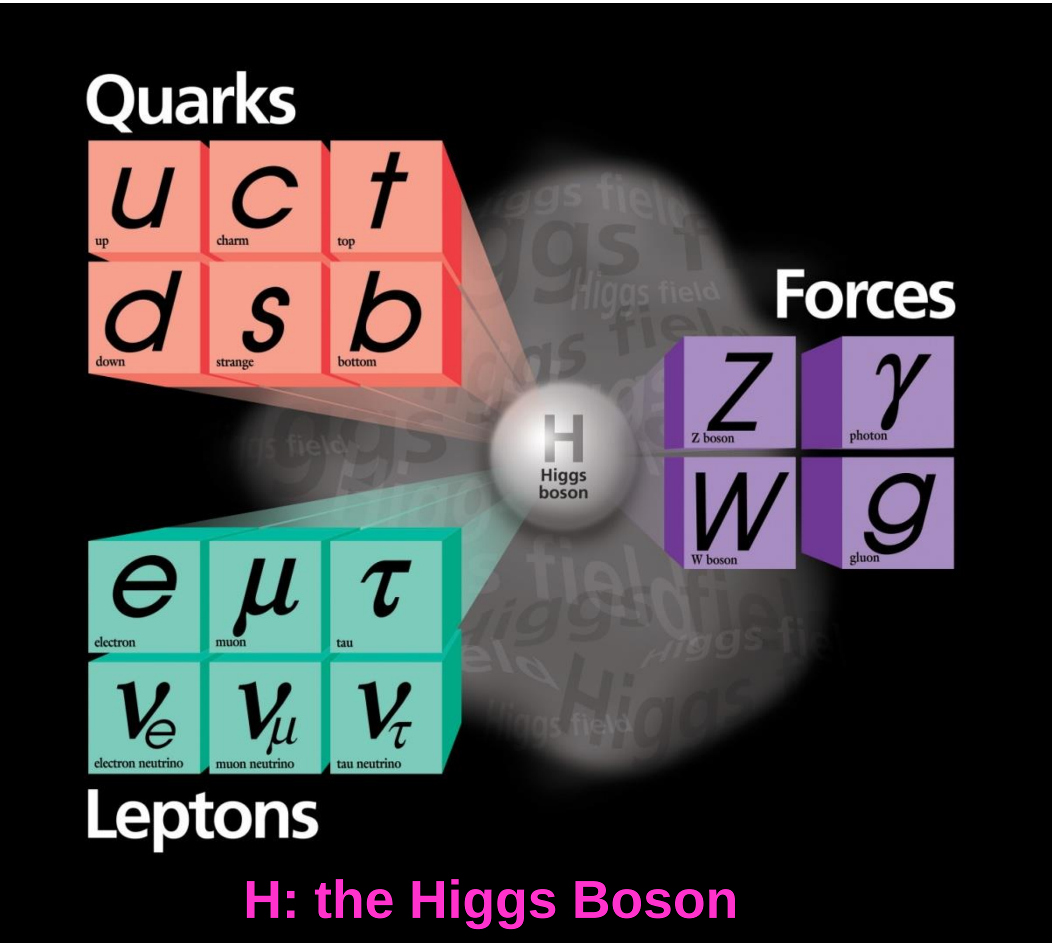


Hadrons

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



The Standard Model



Framework which includes:

Matter
- 6 quarks
- 6 leptons

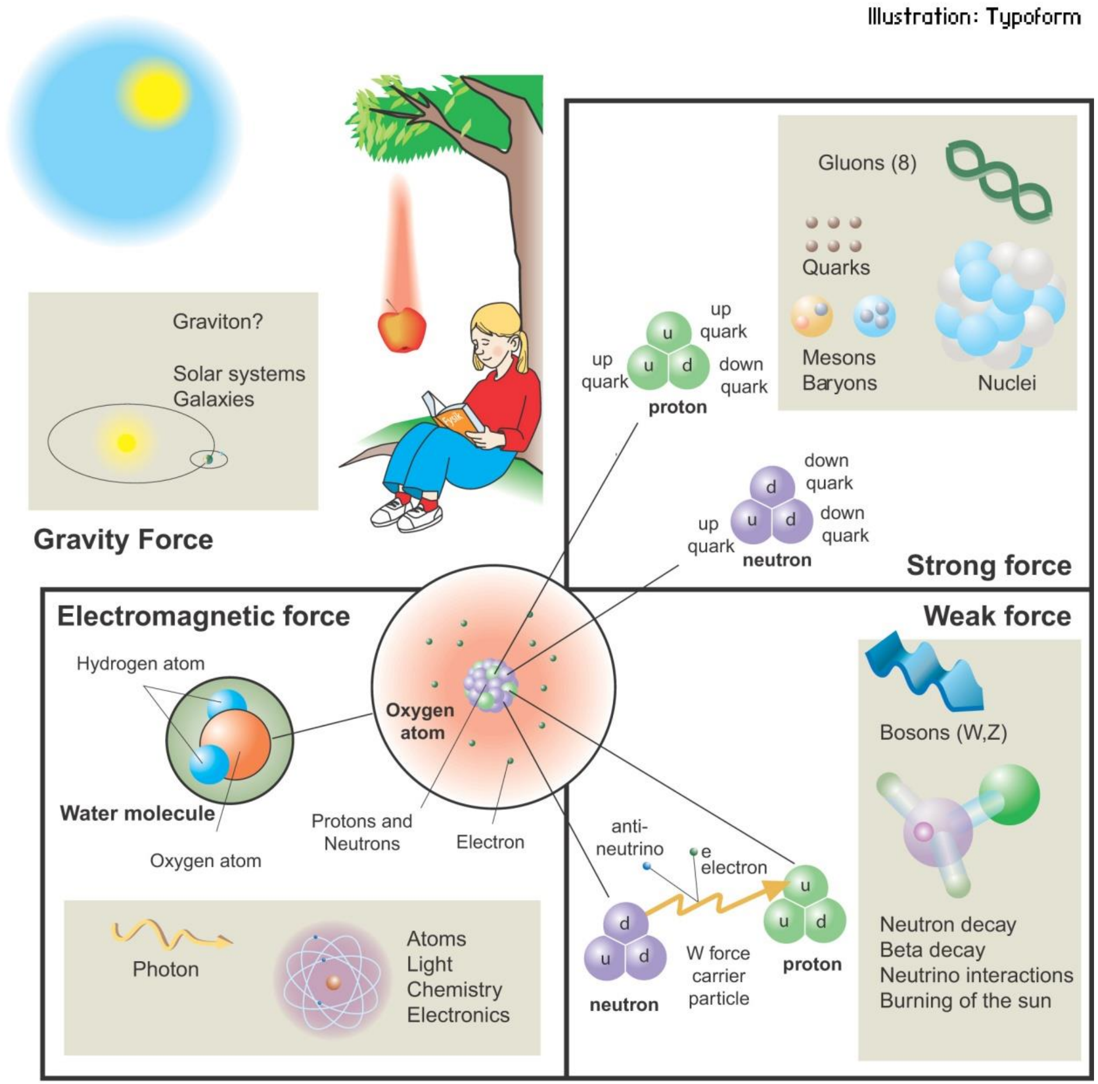
Grouped in three generations

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

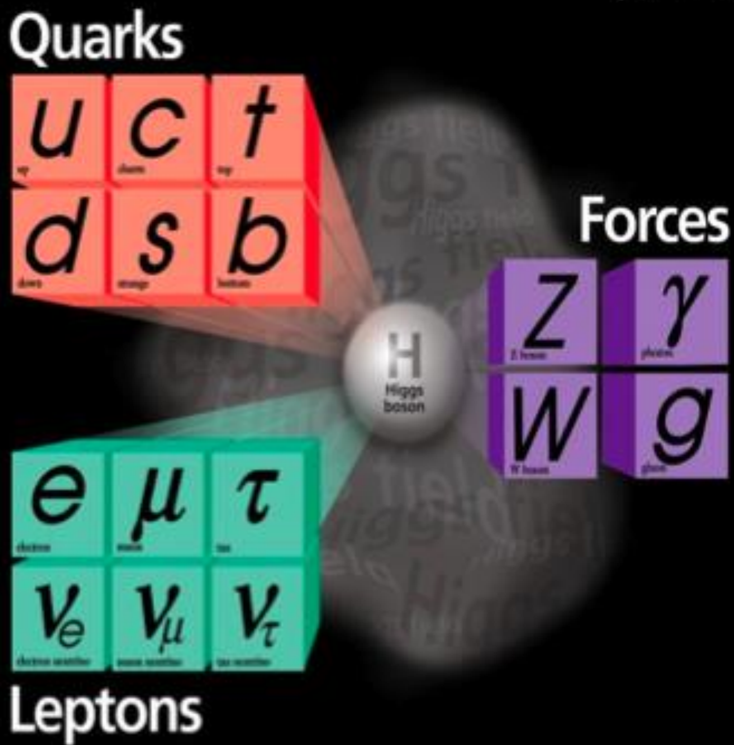
Not gravity! No quantum field theory of gravity yet..

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

The Four Fundamental Forces



The Standard Model and our world

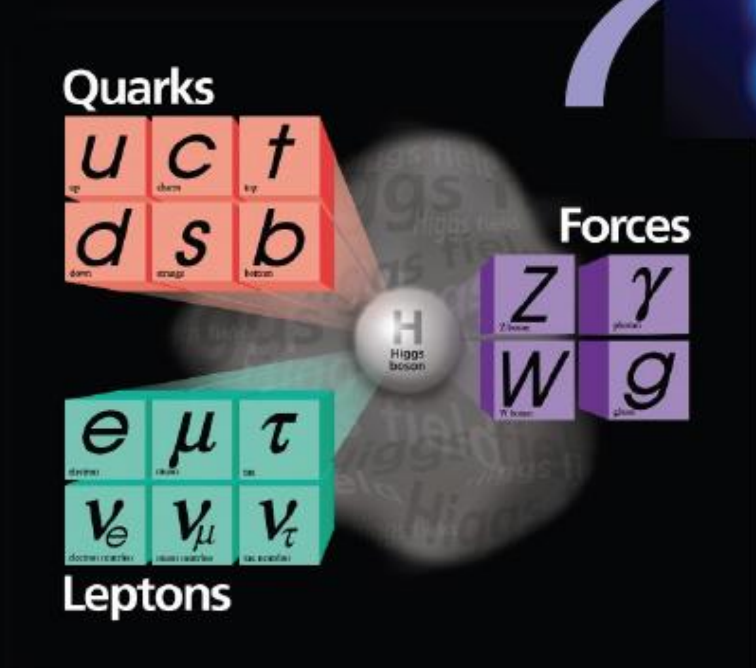


From the D. Gross Nobel Lecture (2004):

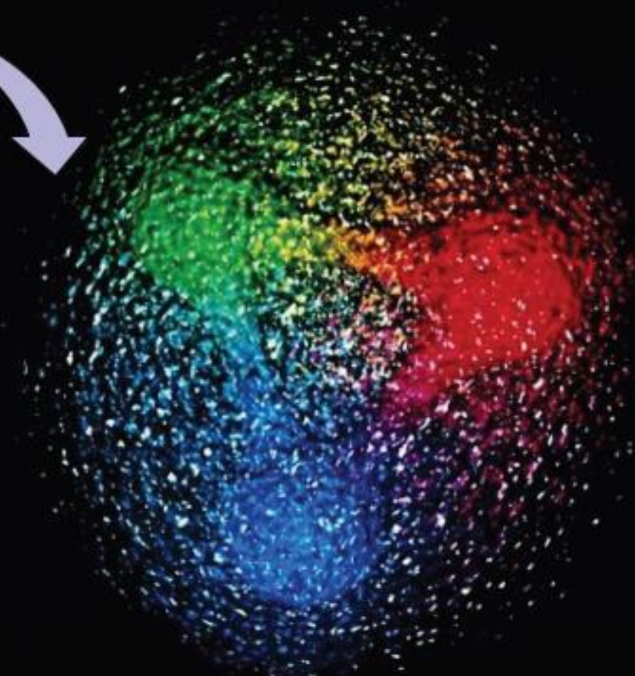
"It is sometimes claimed that the origin of mass is the Higgs mechanism that is responsible for the breaking of the electroweak symmetry that unbroken would forbid quark masses.
This is incorrect. **Most, 99%, of the proton mass is due to the kinetic and potential energy of the massless gluons and the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

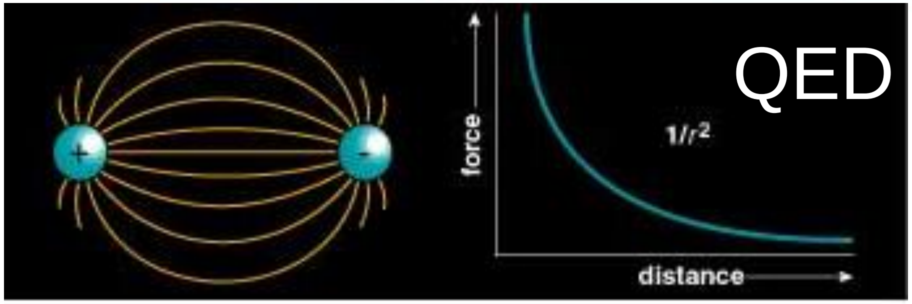
Proton Spin : Only 25% of the proton spin is carried by the quarks

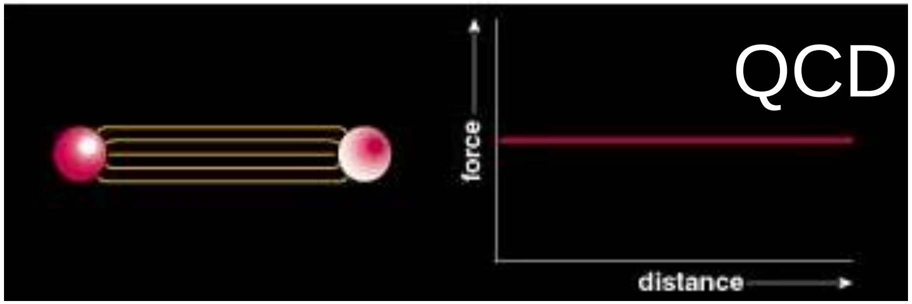
Quantum ChromoDynamics (QCD)

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

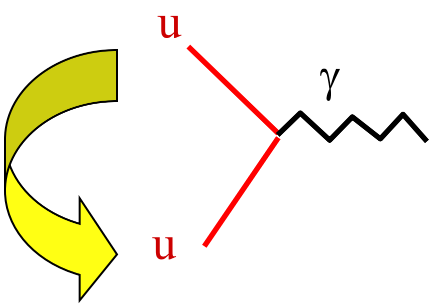
- Gluons couple only to objects that have "color": quarks and gluons
- There are three different charges ("colors"): red, green, blue.
- There are eight different gluons. gluon exchange can change the color of a quark but not its flavor.

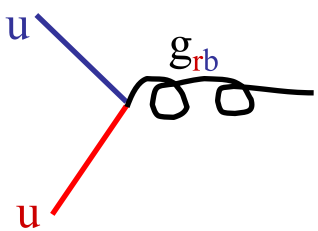
e.g. a red u-quark can become a blue u-quark via gluon exchange.

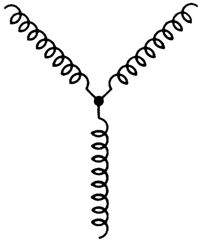


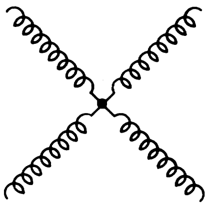


The gluons of QCD carry color charge and interact strongly (in contrast to the photons of QED).









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

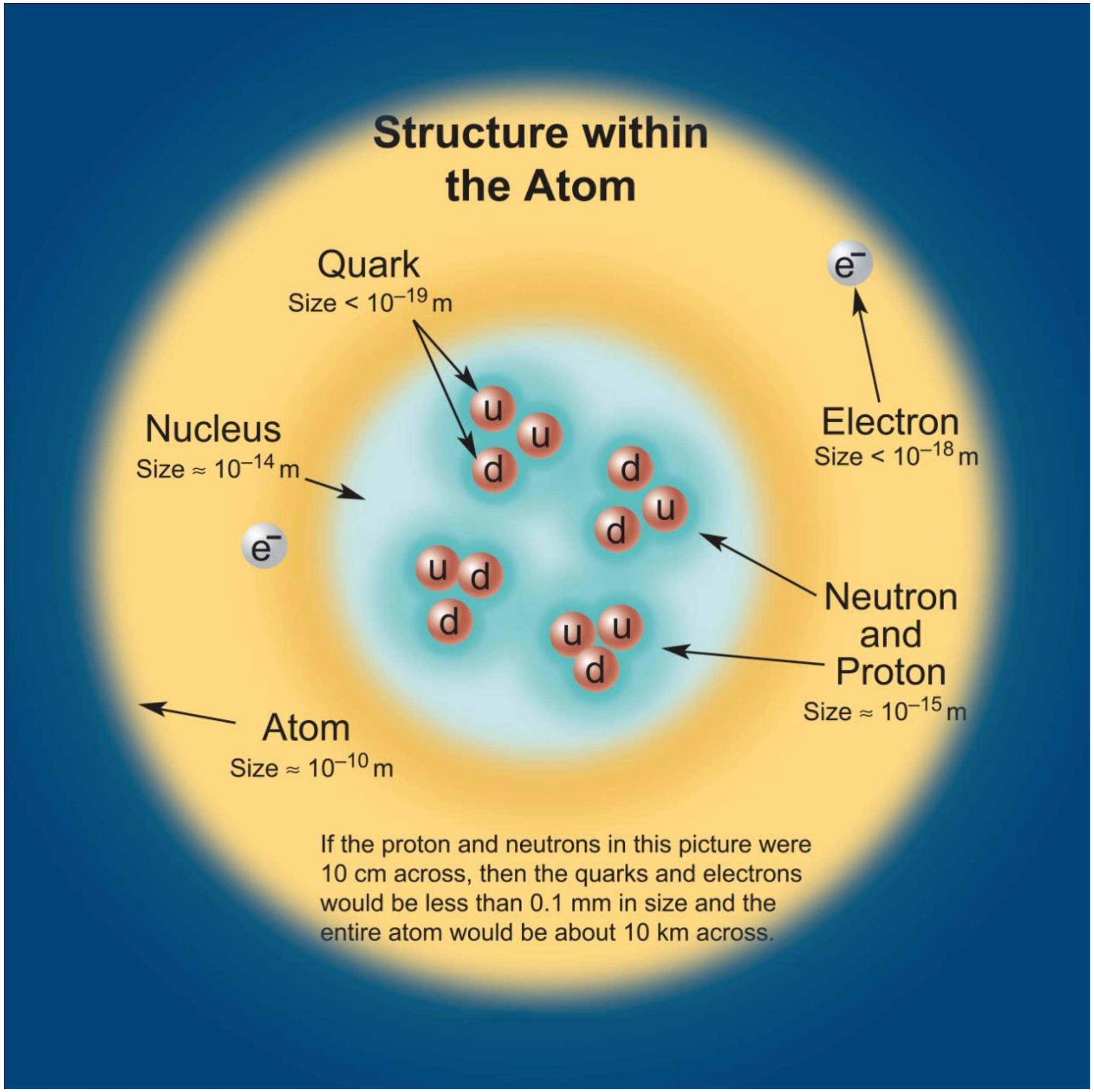
H. David Politzer

Frank Wilczek

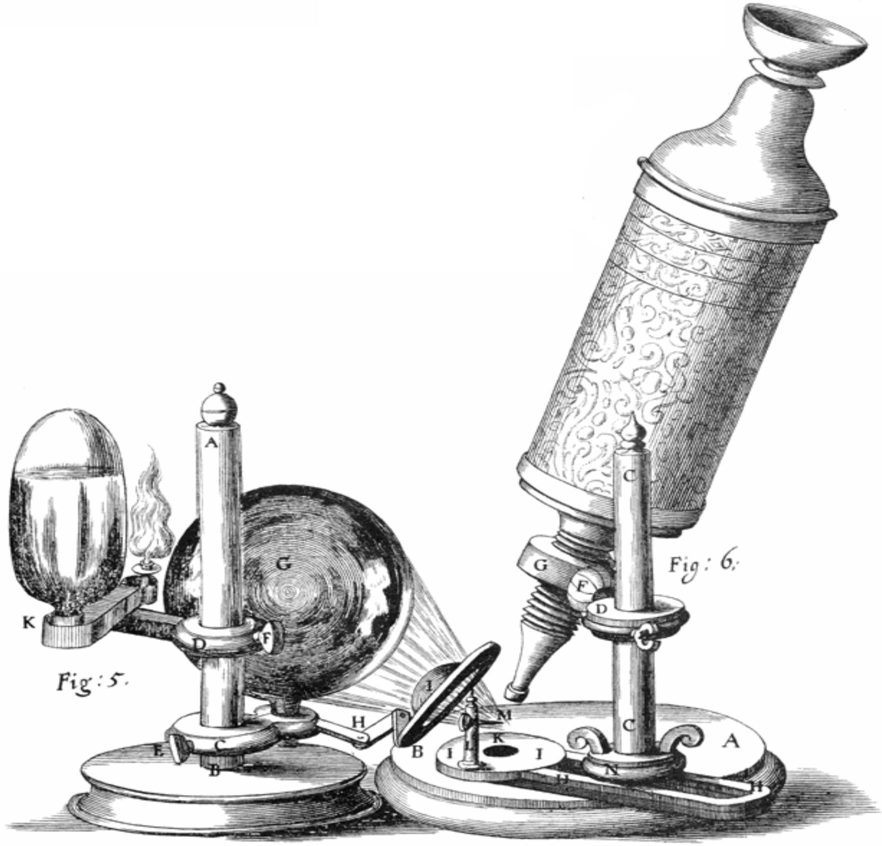
Asymptotic freedom: As the distance between two quarks asymptotically approaches zero, the force becomes arbitrarily weak and the quarks appear to be free. Similarly quarks at very high energies appear to exist as free particles,

A 'colourful' discovery in the world of quarks

From the Atom to the quark



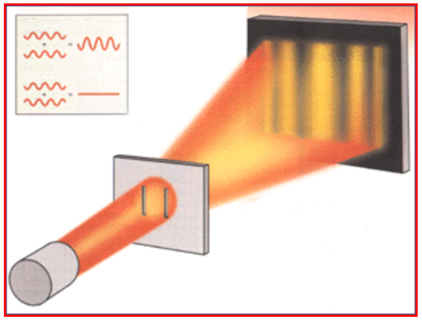
Atoms and sub-atomic particles are much smaller than visible light wave-length
Therefore, we cannot really "see" them (all graphics are artist's impressions)
To learn about the sub-atomic structure we need particle accelerators

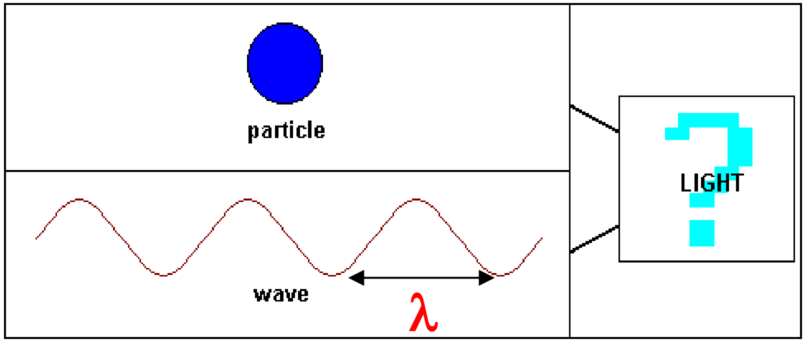


Part –II
Electron Scattering Microscope on the world of quark

Wave-particle duality of Nature

Central concept of quantum mechanics:
all particles present wave-like properties





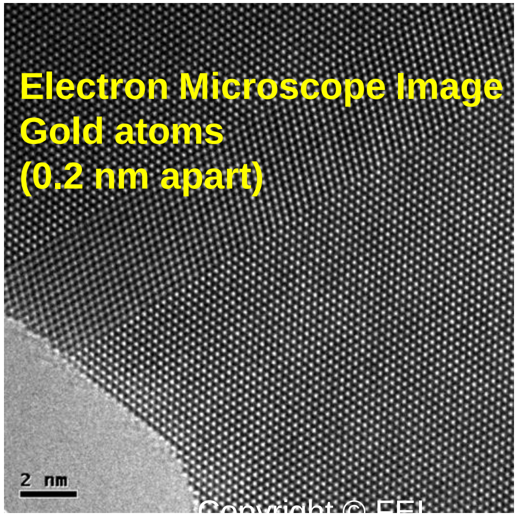
Not only light has a dual nature

De Broglie showed that moving particles have an equivalent wavelength λ

$$\lambda \propto \frac{1}{p}$$

So high momentum gives us short wavelengths so we can make out small details

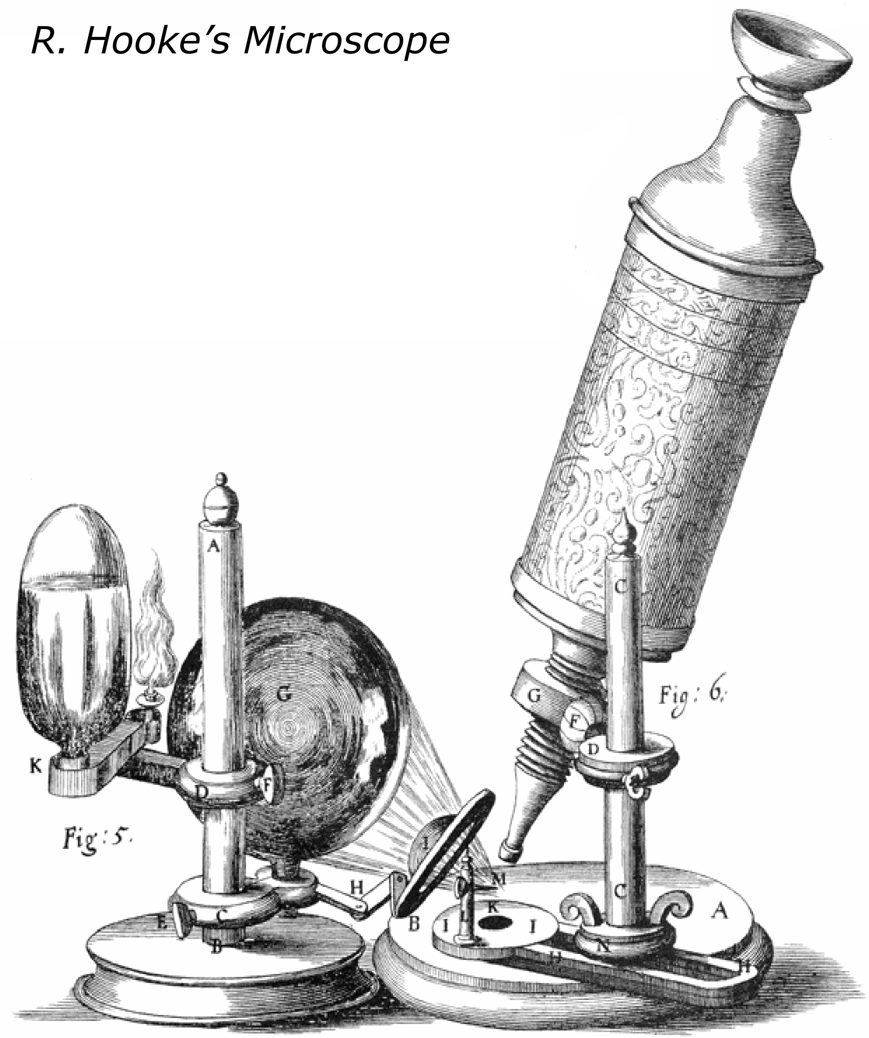
Example: electron microscope



The Microscope

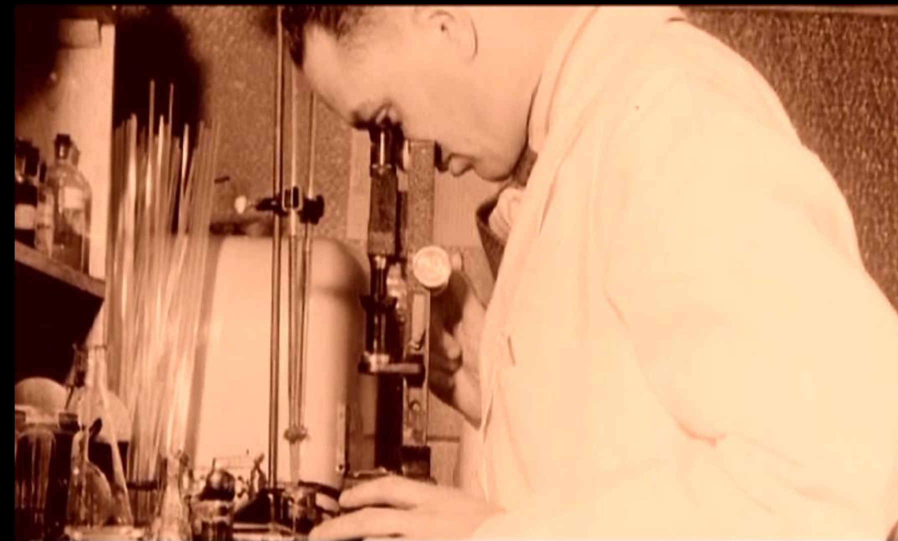
In the past, scientists tried to study microscopic objects invisible to the human eye, using magnifying glasses first and then ever more sophisticated tools

R. Hooke's Microscope

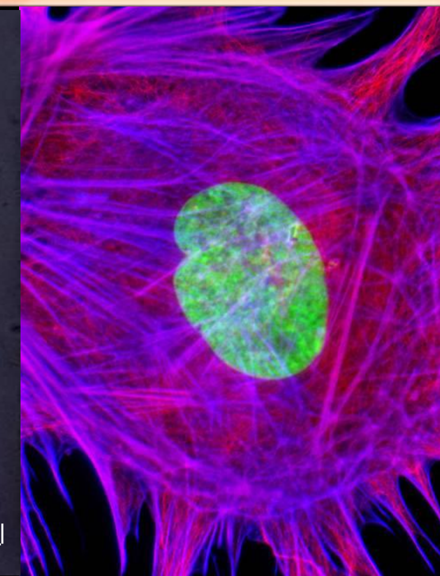


The Microscope

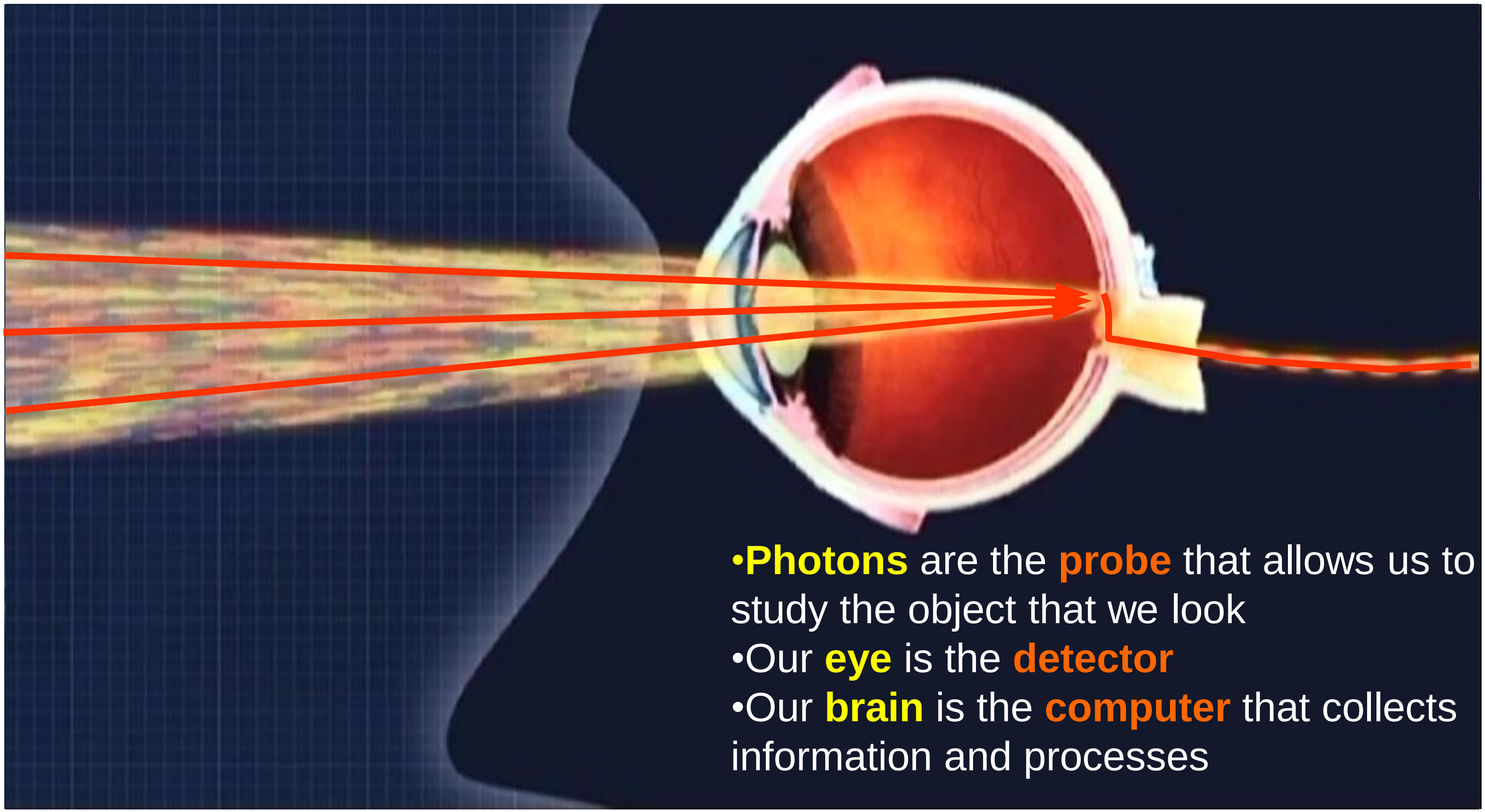
In the past, scientists tried to study microscopic objects invisible to the human eye, using magnifying glasses first and then ever more sophisticated tools



The optical microscope allowed the discovery of the existence of microscopic organisms and to study the organic fabric



The Microscope

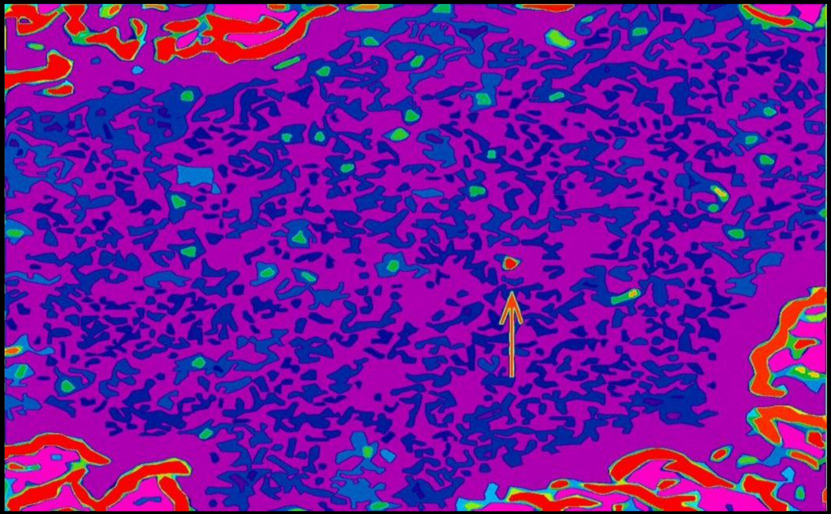


- **Photons** are the **probe** that allows us to study the object that we look
- Our **eye** is the **detector**
- Our **brain** is the **computer** that collects information and processes

The Microscope

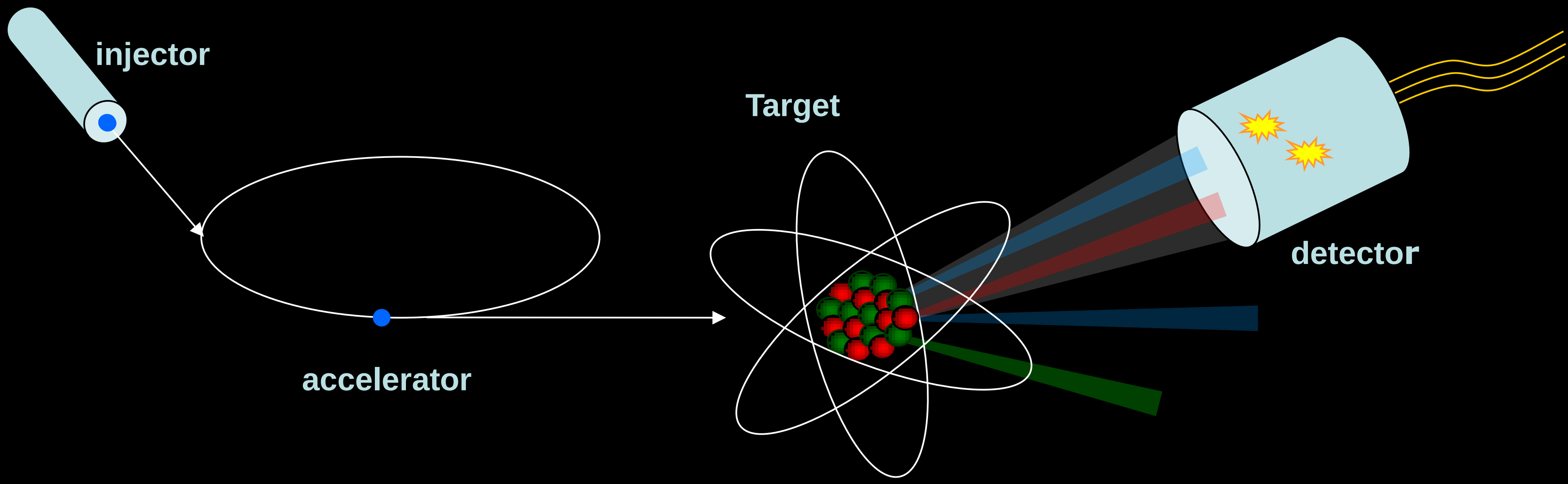
Today, more sophisticated microscopes achieved a very high resolution

the electron microscope allows you to see objects the size of the atom

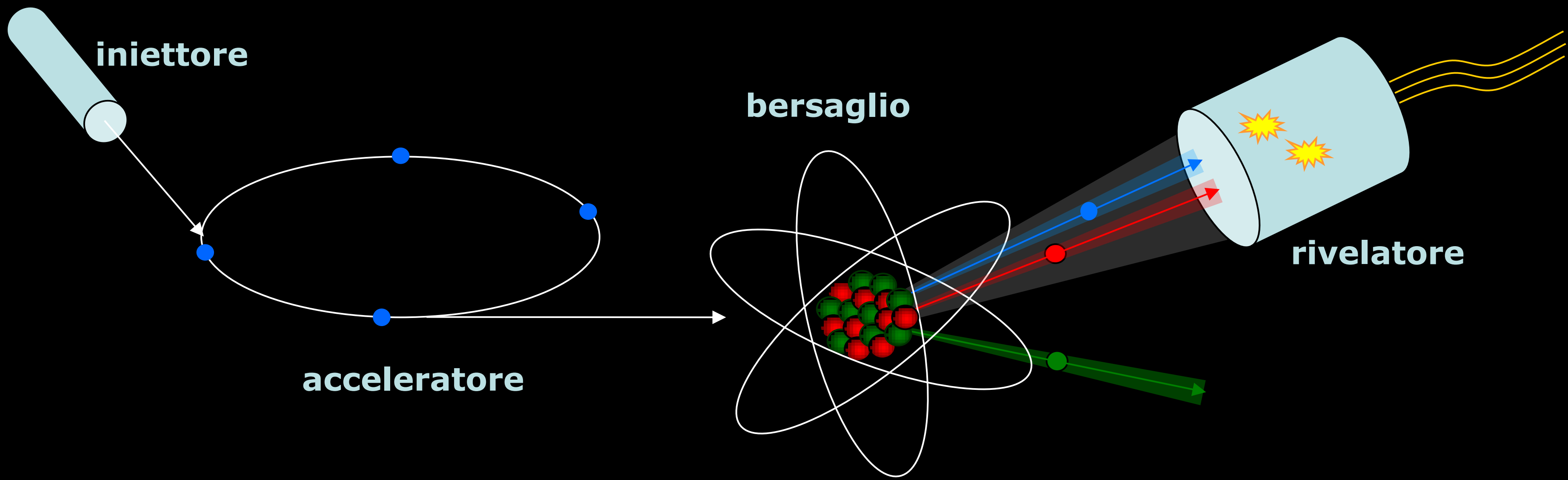


But how can we get to "see" quarks?

Electron Scattering

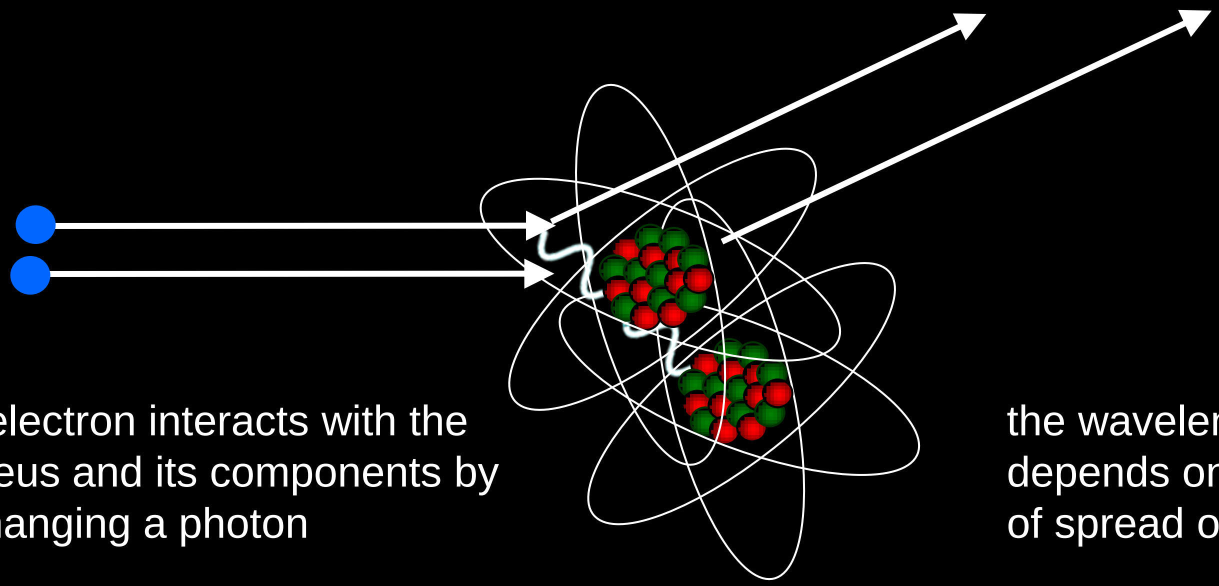


la diffusione di elettroni



but what happens when an electron interacts with the nucleus and with the protons and neutrons inside?

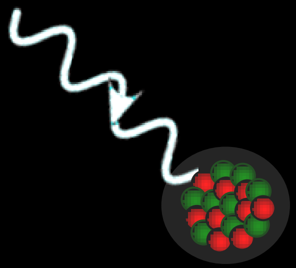
Electron Scattering



the electron interacts with the nucleus and its components by exchanging a photon

the wavelength of the photon depends on the energy and the angle of spread of the electron

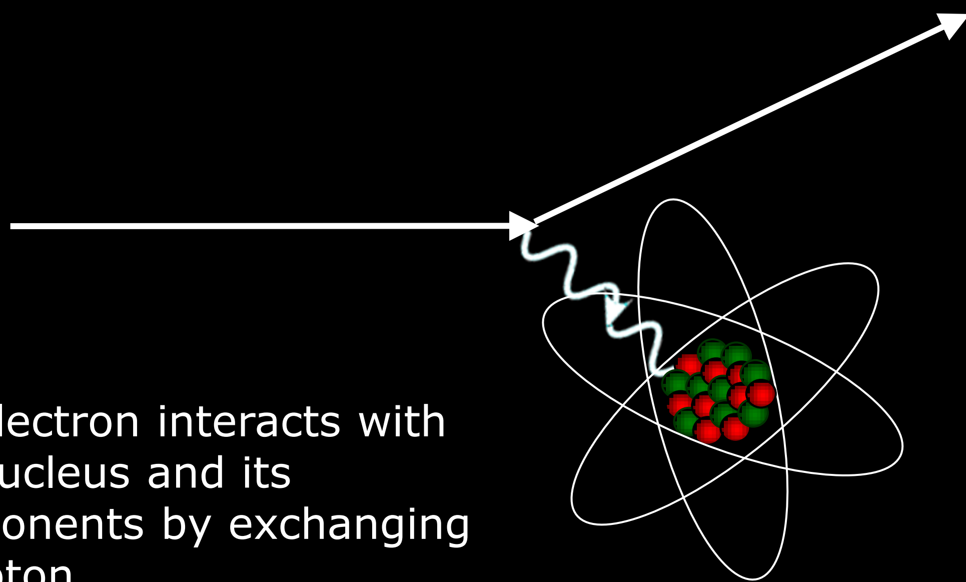
At wavelengths comparable to the size of the nucleaus



the photon interacts with the entire core and it is not possible to distinguish its components

$\lambda >> 10^{-15}$ m

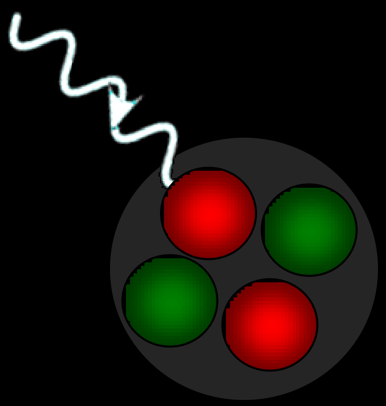
Electron Scattering



the electron interacts with the nucleus and its components by exchanging a photon

the wavelength of the photon depends on the energy and the angle of the electron

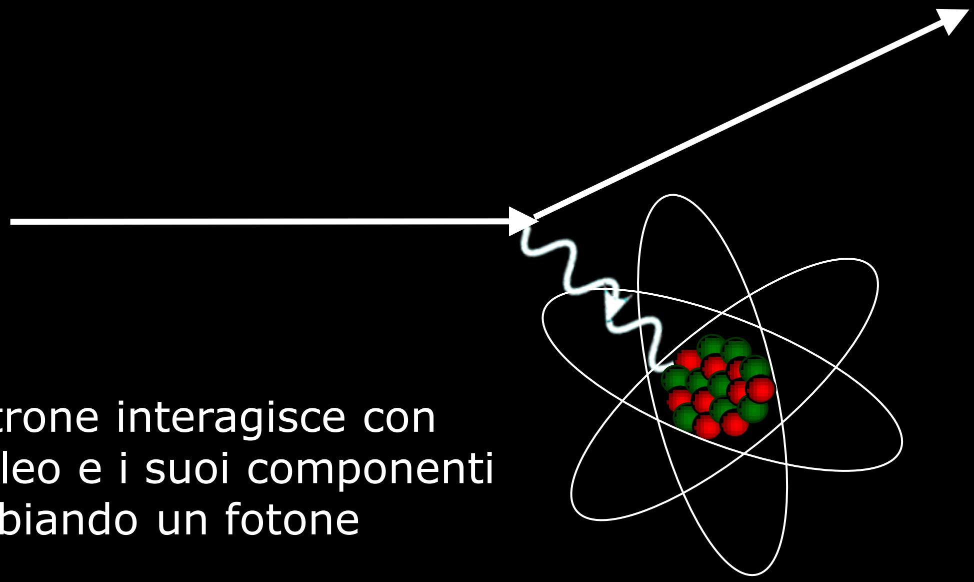
At intermediate wavelength the order of the size of the nucleon



the photon interacts with the individual protons and neutrons that make up the nucleus

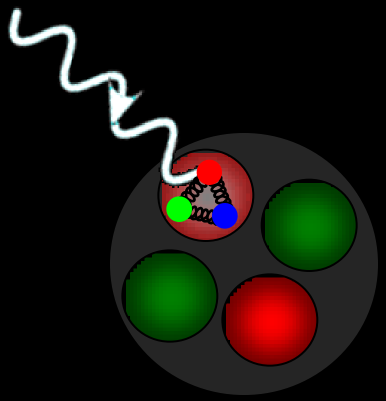
$\lambda \sim 10^{-15}$ m

Electron Scattering



l'elettrone interagisce con
il nucleo e i suoi componenti
scambiando un fotone

the wavelength of the photon
depends on the energy and the angle
the electron

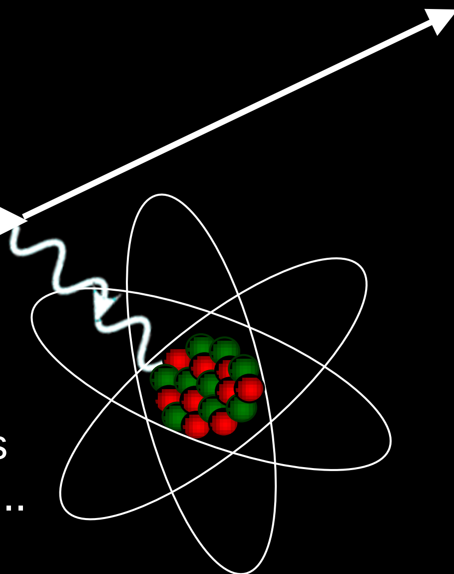


At short wavelength, smaller
than the size of the proton

the photon interacts with the
constituents of the individual
nucleons, ie quarks and gluons

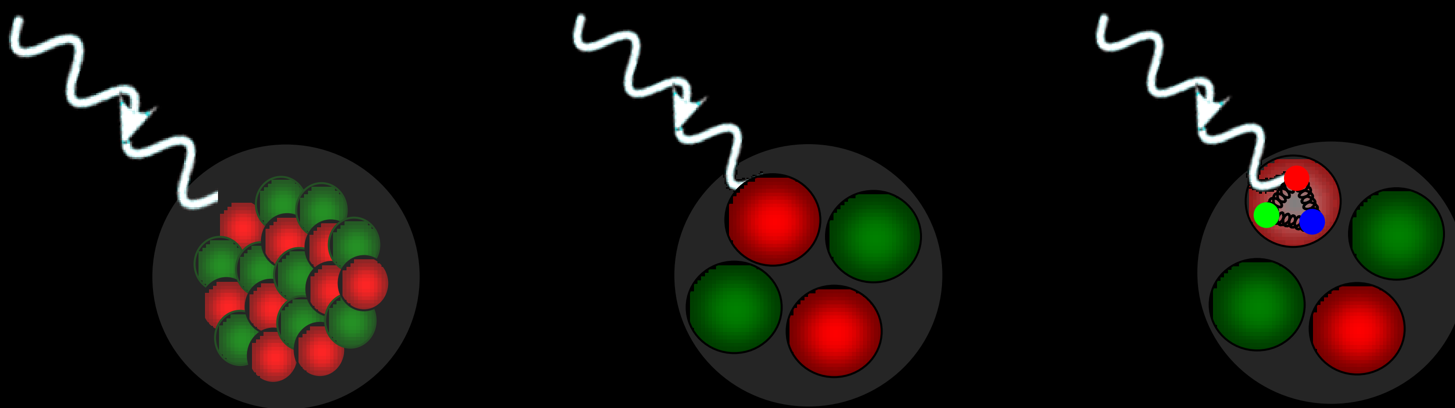
$\lambda << 10^{-15}$ m

Electron Scattering



Varying the wavelength we can probe the atomic nucleus and its components at different depths ...

And ... study how quarks and gluons form nucleons and nuclei



$\lambda >> 10^{-15}$ m　　$\lambda \sim 10^{-15}$ m　　$\lambda << 10^{-15}$ m

Why use electrons?

- Why not alpha's or protons or neutrons?
- Why not photons?

Alphas, protons or neutrons have two disadvantages

(1) They are STRONGLY INTERACTING – and the strong force between nucleons is so mathematically complex (not simple $1/r^2$

(2) They are SIZEABLE particles (being made out of quarks). They have spatial extent – over ~1F. For this reason any diffraction integral would have to include an integration over the "probe" particle too.

Photons have a practical disadvantage: They could only be produced at this very high energy at much greater expense. First you would have to produce high energy electrons, then convert these into high energy positrons – which then you have to annihilate. And even then your photon flux would be very low.

Why use electrons?

- Why not alpha's or protons or neutrons?
- Why not photons?

Electrons are very nice for probing the nucleus because:

(1) They are ELECTRO-MAGNETICALLY INTERACTING – and the electric force takes a nice precise mathematical form ($1/r^2$)

(2) They are POINT particles ($<10^{-3}$ F – probably much smaller). [Like quarks they are considered to be "fundamental" particles (not composites)]

(3) They are most easily produced and accelerated to high energies

Electron Scattering

Electron scattering has also some disadvantages:

- The interaction is "weak", so cross sections are small

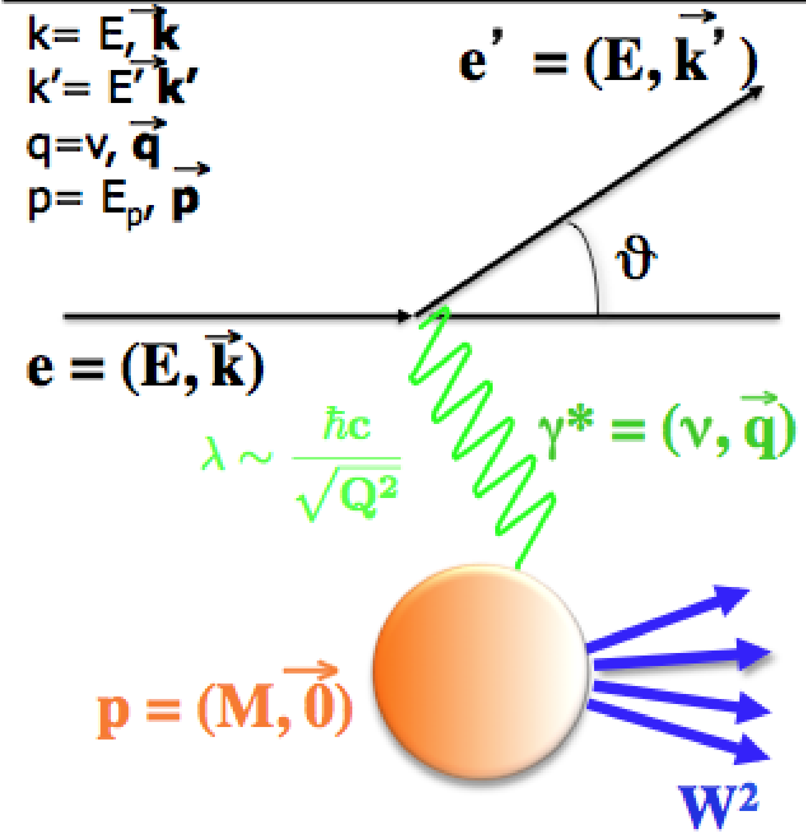
High Luminosity

- Because electrons are very light particles, they easily emit radiation (so- called Bremsstrahlung). This gives rise to radiative tails, with often large corrections

Can be calculated exactly in QED

Used as interference to enhance some processes

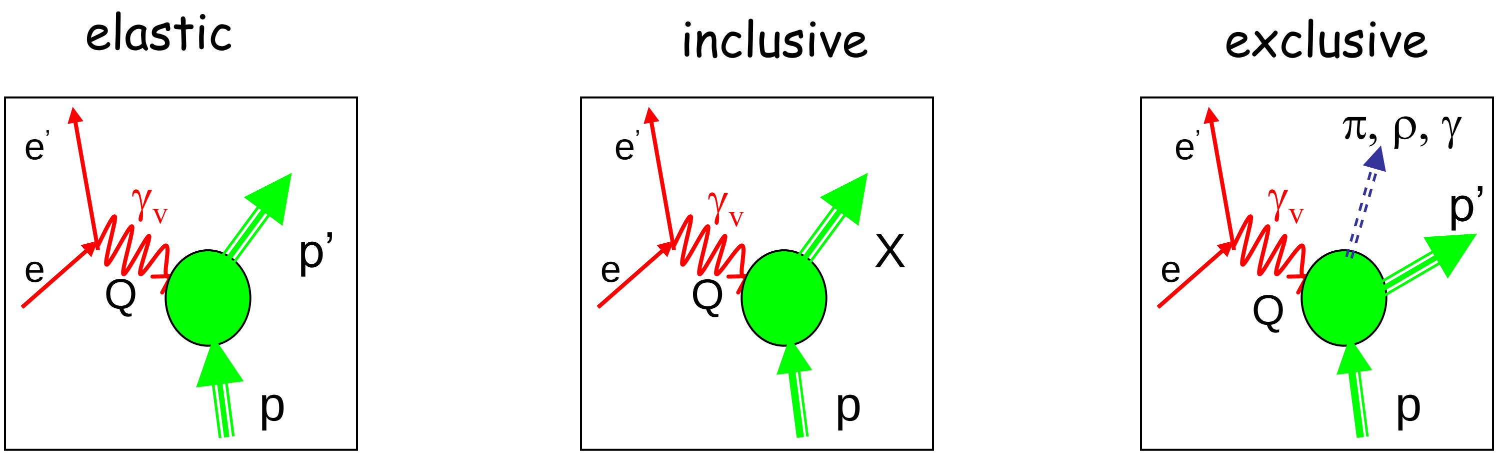
Electron Scattering: Kinematics



$W^2 = M^2$ $X_B = 1$ elastic scattering
$W^2 \neq M^2$ $X_B < 1$ inelastic scattering
$Q^2 \gg M^2$ deep inelastic scattering

Lorentz inv.		Lab frame	Meaning
$q^2 = -Q^2$	$(k - k')^2$	$-4EE' \sin^2(\frac{\theta}{2})$	Virtuality
x_B	$\frac{-q^2}{2p \cdot q}$	$\frac{Q^2}{2M\nu}$	Bjorken scaling variable; Inelasticity of the process
ν	$\frac{p \cdot q}{\sqrt{(p^2)}}$	$E - E'$	Energy lost by the incoming lepton
W^2	$(p + q)^2$	$M^2 + 2M\nu - Q^2$	Inv. mass squared of the final state
y	$\frac{p \cdot q}{p \cdot k}$	$\frac{\nu}{E}$	Fraction of the electron energy carried by the γ^*
s	$(p + k)^2$	$\approx M^2 + 2M\nu$	Center of mass energy

Electron Scattering - Kinematics

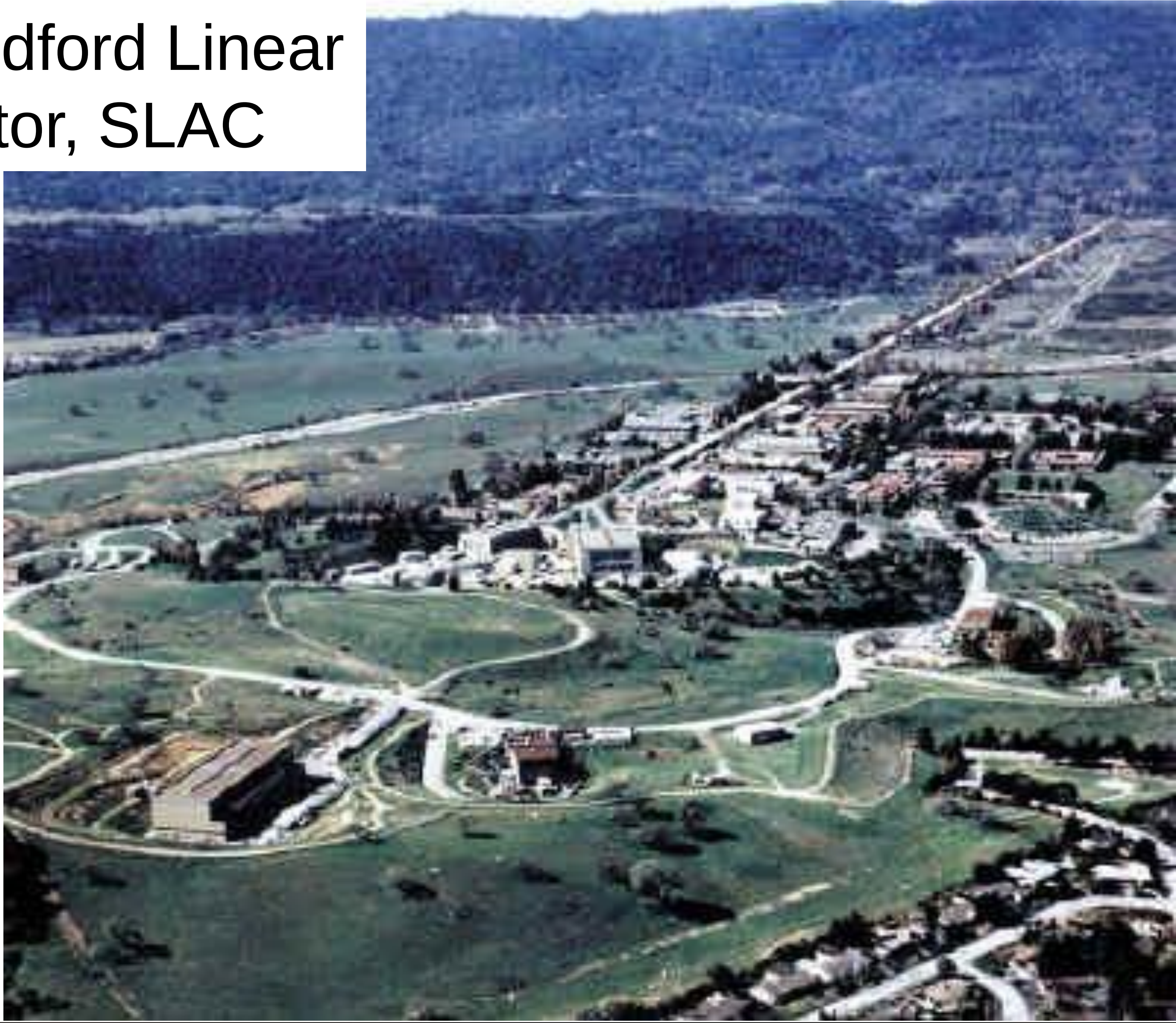


$Q^2 = -(e-e')^2$
$\nu = E_e - E_{e'}$
$x_B = Q^2/2M\nu$
$t = (p-p')^2$

$x_B = 1$ (for elastic scattering)

$1/\sqrt{Q^2}$ is the spatial resolution of the virtual γ

The Standford Linear Accelerator, SLAC



Electron scattering experiments at SLAC 1954 - 57

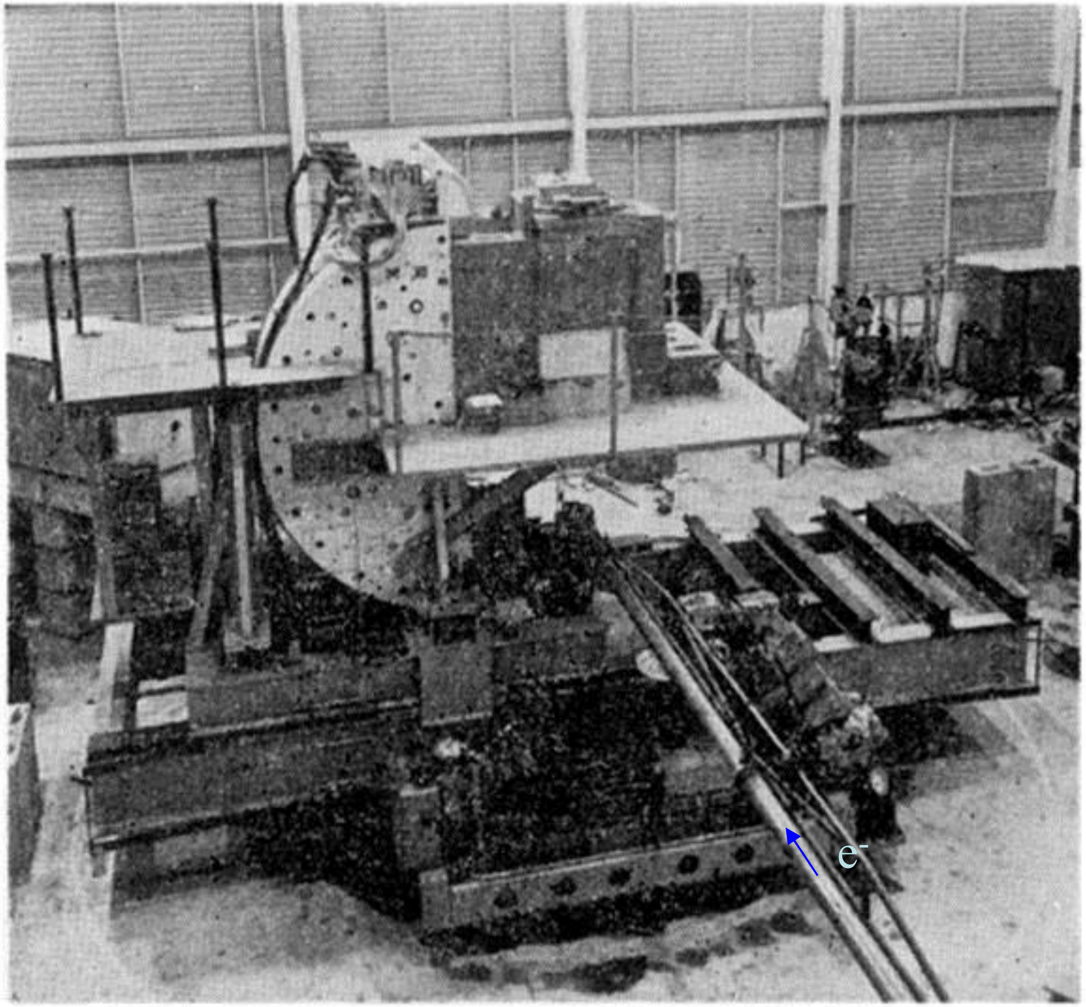


FIG. 19. Photograph of the 550-Mev spectrometer, the gun mount, and shield. The electron beam is brought to the target, shown under the platform, through the vacuum pipe in the foreground.

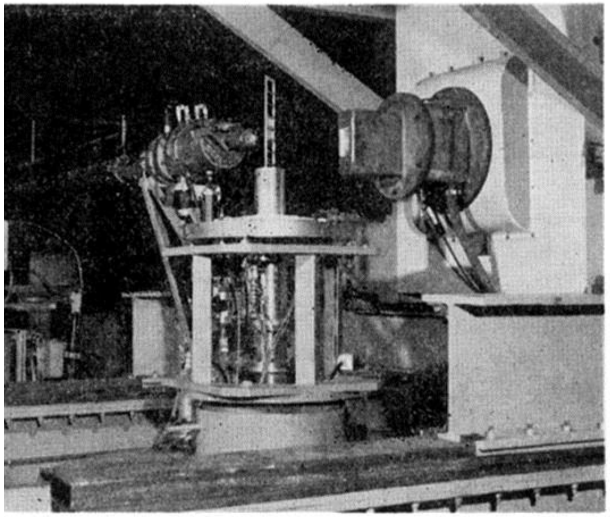
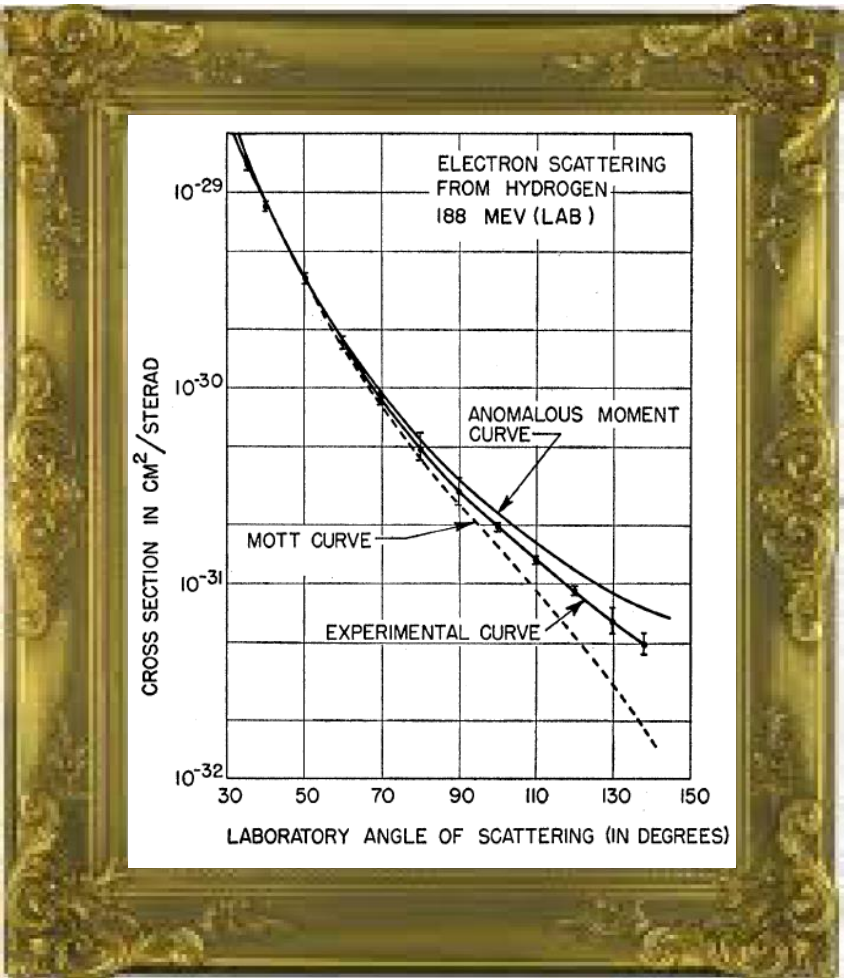


FIG. 22. Details of the monitor, target ladder, and magnet input port.

Does the Proton have finite size?



R. Hofstadter
Was awarded
Nobel Prize 1961

Professor Hofstadter's group worked at SLAC during the 1950s and was the first to find out about the charge distribution of protons in the nucleus – using high energy electron scattering.

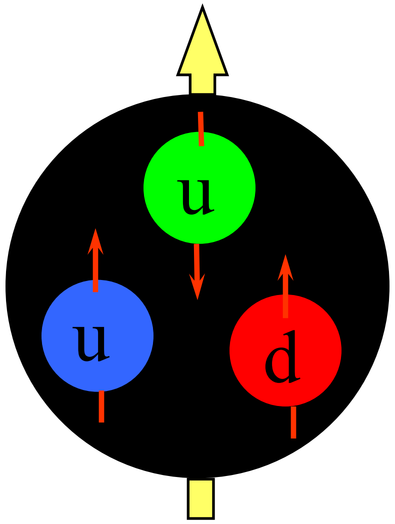
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_M \times \left(G_1(Q^2) + 2\tau G_2(Q^2) tan^2\frac{\theta}{2}\right)$$

$$G_1(Q^2) = \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} \qquad G_2(Q^2) = G_M^2(Q^2)$$

$$\left(\frac{d\sigma}{d\Omega}\right)_M = \frac{4\alpha^2 E'^2}{Q^4} cos^2\frac{\theta}{2}\frac{E'}{E} \qquad \tau = \frac{Q^2}{4M^2}$$

- Elastic electron-proton scattering ⇨ the proton is not a point-like particle, it has finite size.

Constituent Quark model



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

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

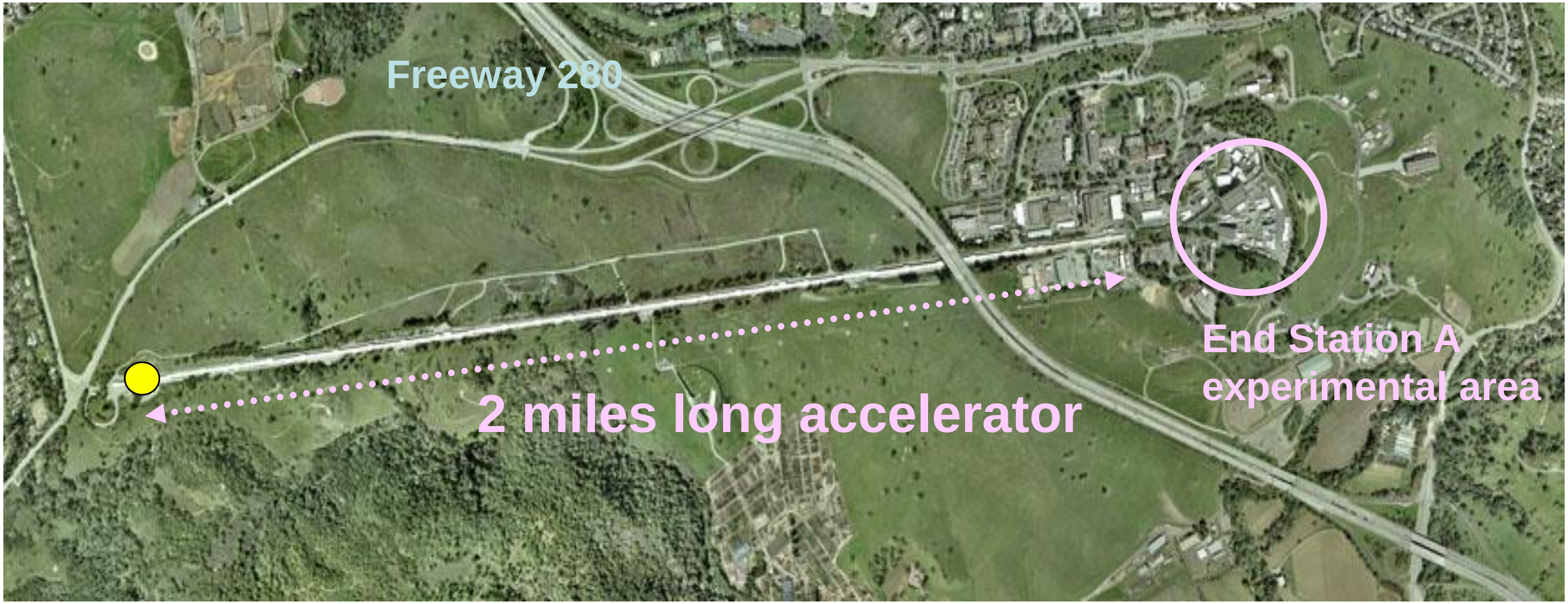
- Proton mass: $m_p \approx 3m_q$
- Proton spin: $\vec{S} = \frac{\vec{1}}{2} \oplus \frac{\vec{1}}{2} \oplus \frac{\vec{1}}{2}$

Solely built from the quark spins!

Tremendously successful model in description of

- Hadron mass spectra

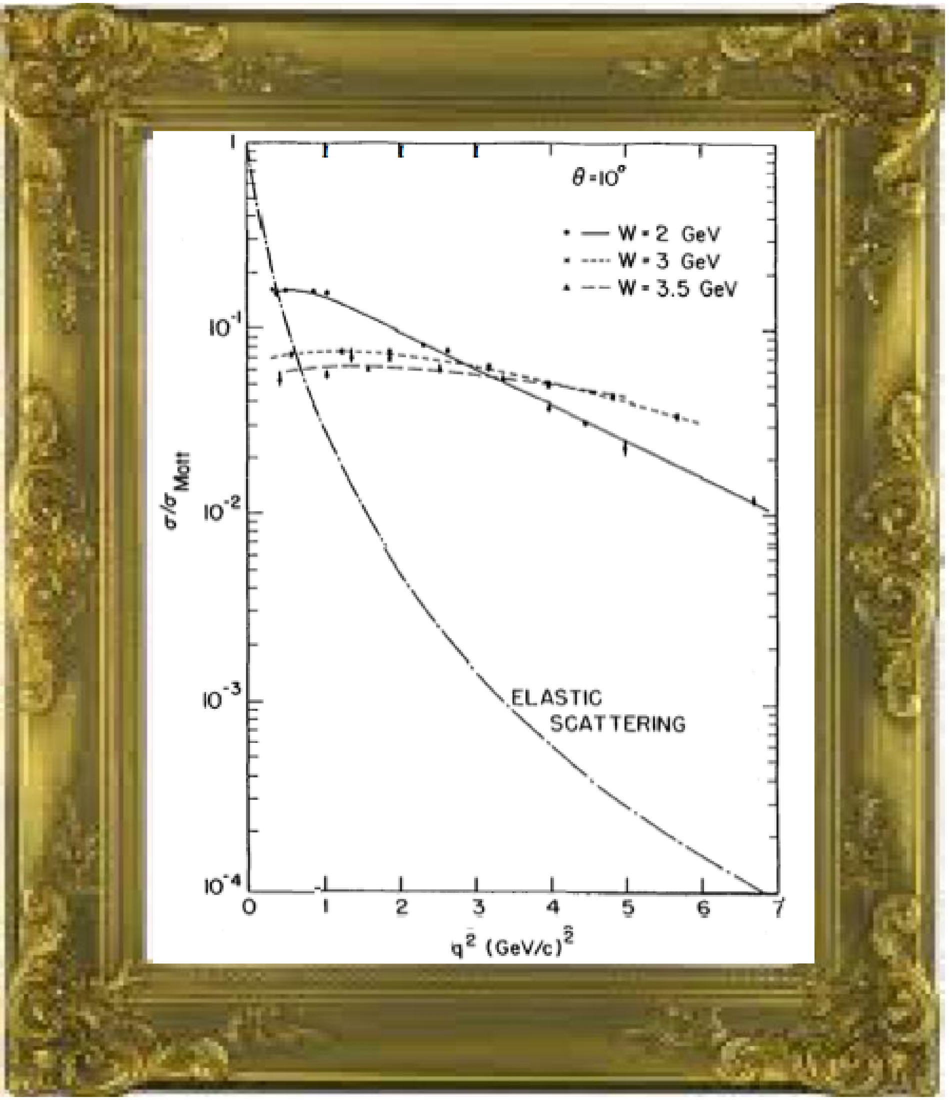
Quarks detected within protons



Stanford (SLAC), California, late 1960s

Fire electrons at proton: big deflections seen!

What is the internal structure of the proton?



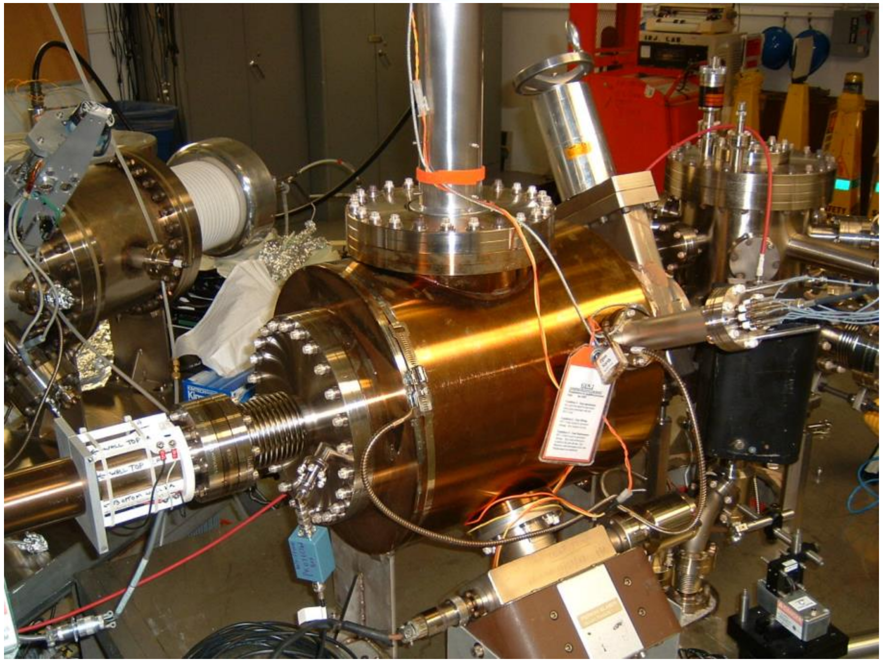
Nobel prize 1990

J. Friedman H. Kendall R. Taylor

Deep Inelastic Scattering (DIS) cross section almost independent of Q^2

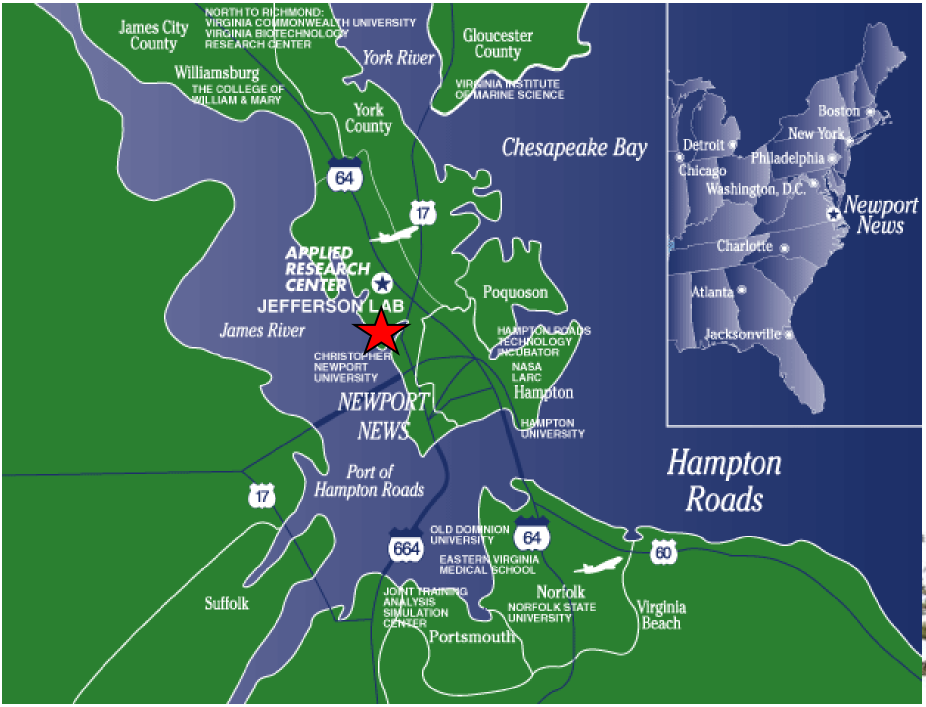
Scaling → Quarks are point-like objects!

Determine quark momentum distribution f(x).



Next generation of Electron Accelerator CEBAF (Jefferson Lab)

Jefferson Lab

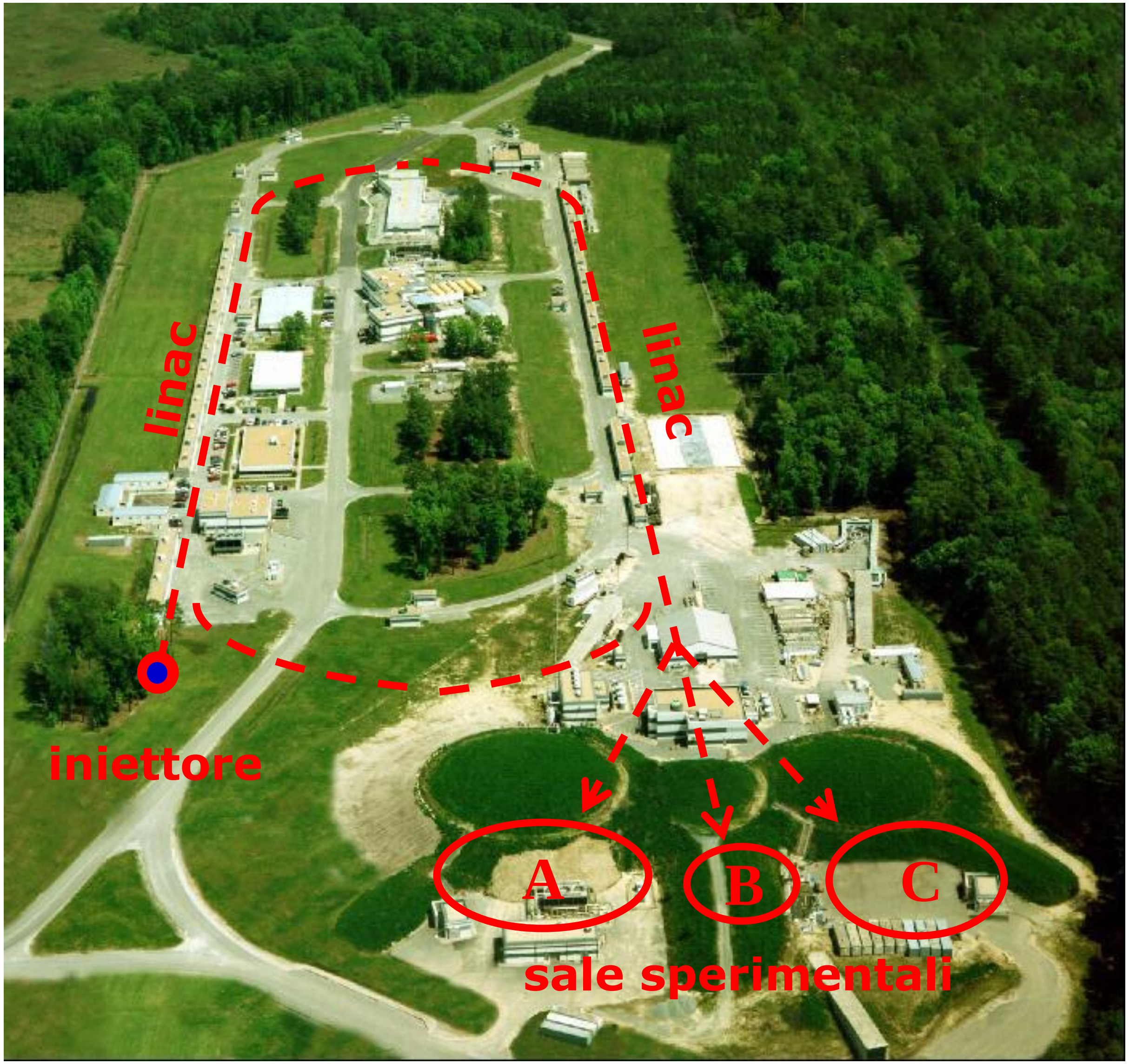


- Jefferson laboratory is located Newport News (VA) (USA)
- Construction started in 1987
- Funded by the Department of Energy
- Started operation in 1997

Superconducting accelerator of electrons with maximum energy 6 GeV from 1997-2012

Upgrade to 12GeV is underway to sart operation in 2015

CEBAF



Continuous

Electron

Beam

Accelerator

Facility

→ E: 0.75 – 6 GeV

→ I_{max}: 200mA

→ **Duty Cycle: ~ 100%**

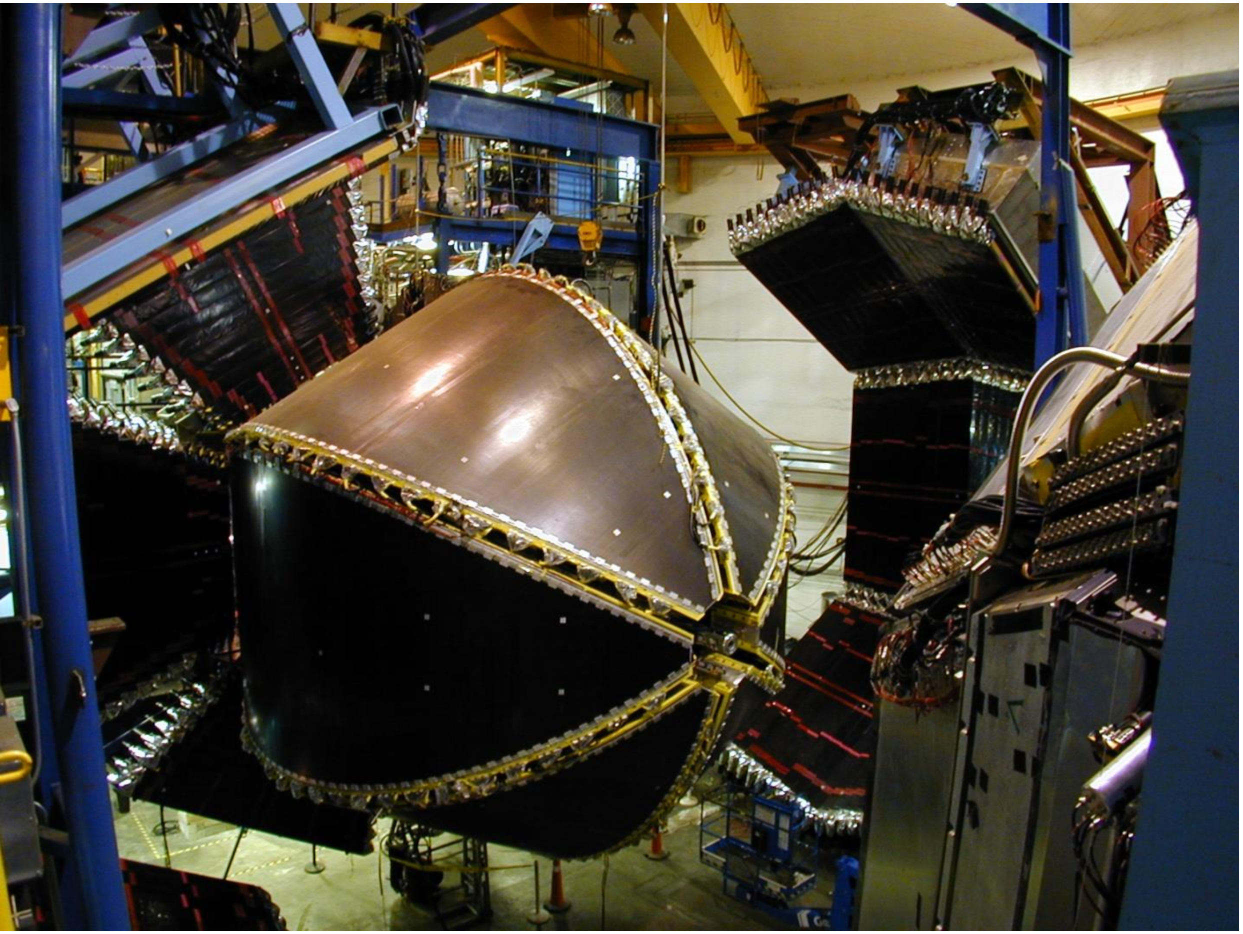
→ $\sigma(E)/E$: 2.5×10^{-5}

→ **Polarization: 80%**

→ Deliver beam to 3 experimental Halls (A, B,C)simulatanuously

CEBAF Large Acceptance Detector (CLAS)

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.

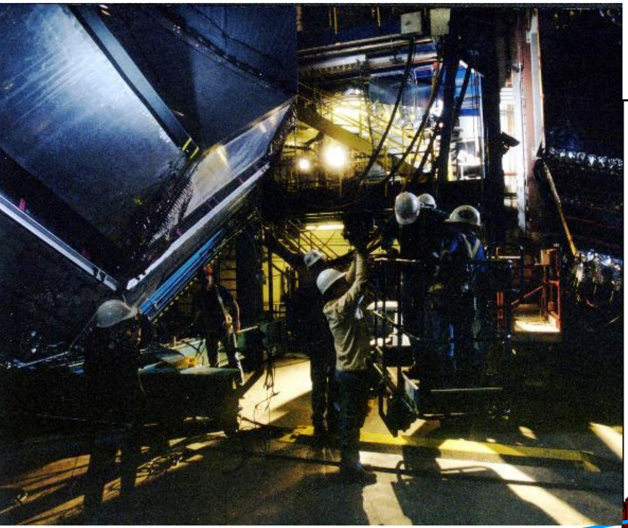
Scientist from all around the world used this detector to conduct experiments to better understand the interactions between quarks and gluons, that hold quarks together to form protons and neutrons

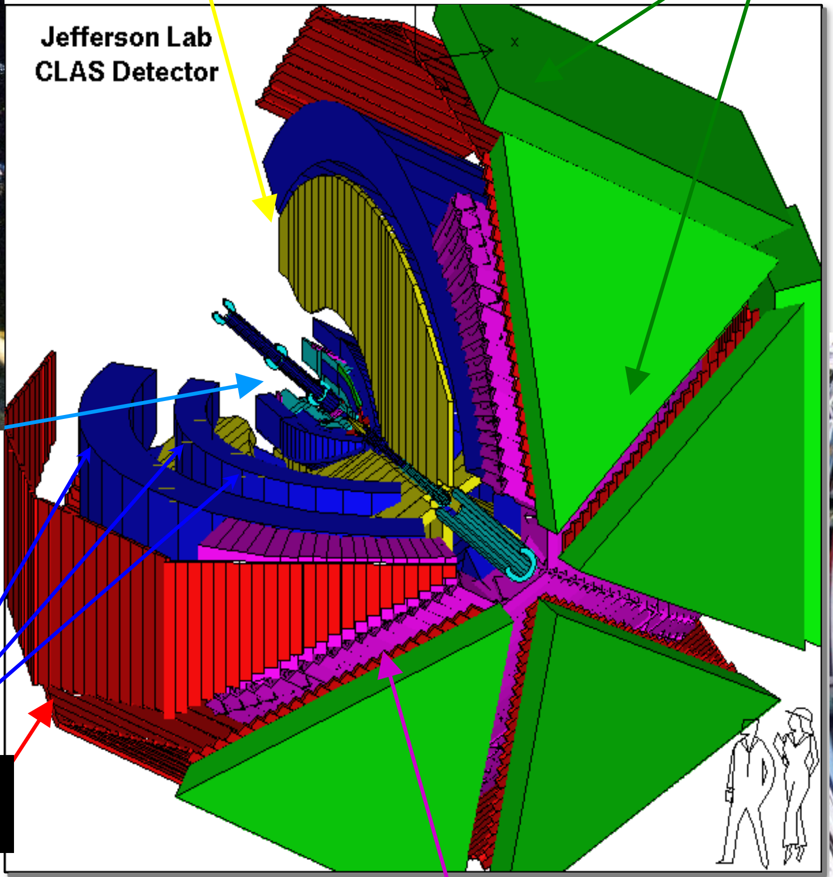
CEBAF Large Acceptance Spectrometer

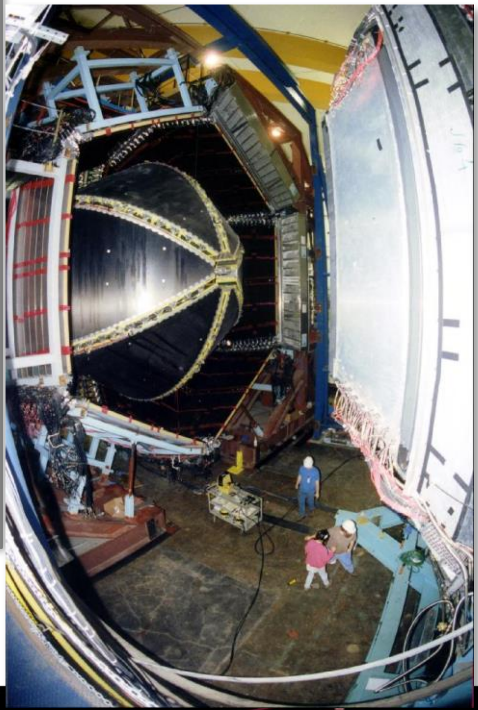
Torodial Magnet

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

The CLAS Collaboration

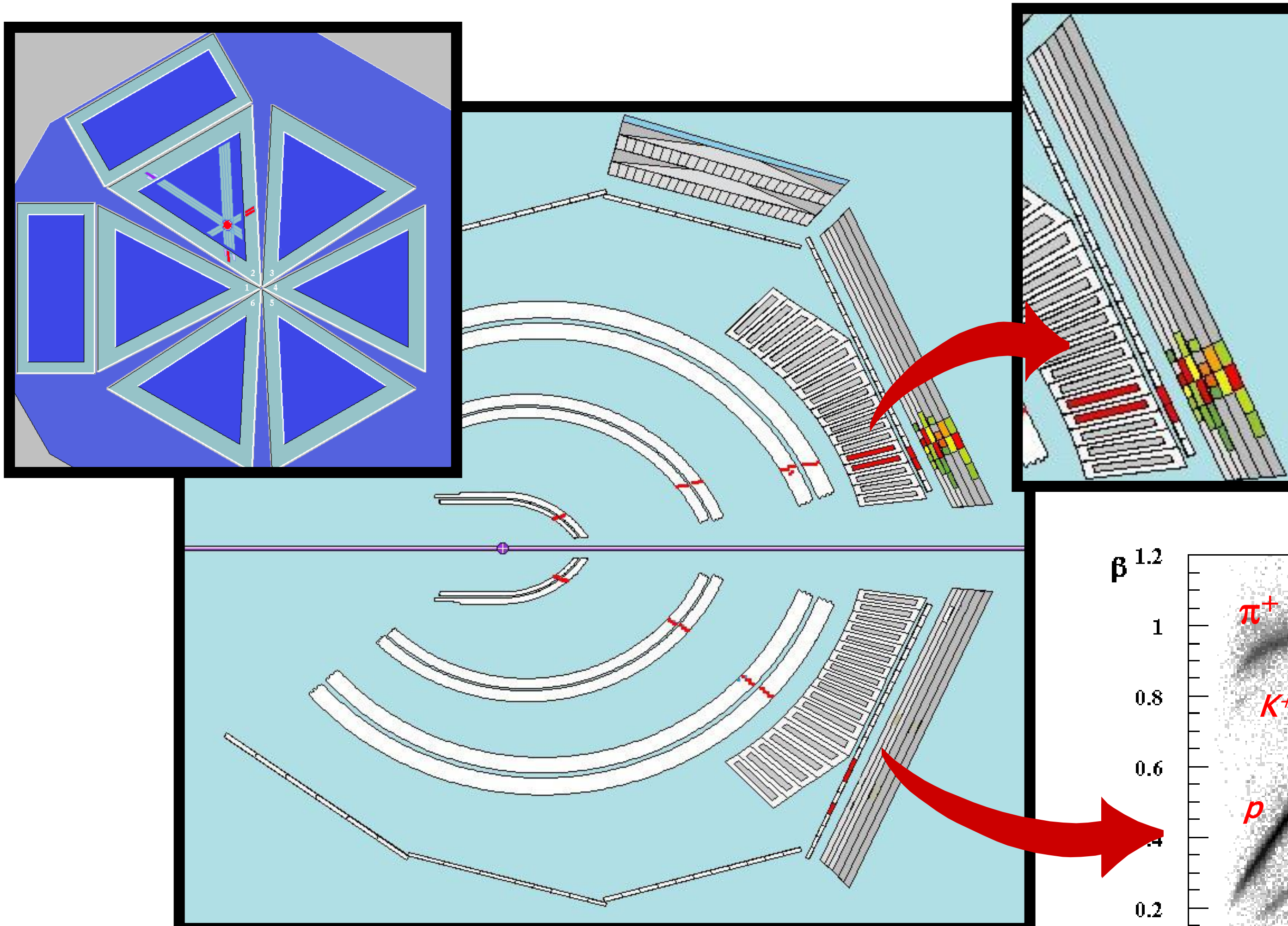
Hall Leader: *Volker burkert*
CLAS Collaboration
Chair: *David Irlan (Glascow)*

Argonne National Laboratory, Argonne, IL
Arizona State University, Tempe, AZ
Canisius College, Buffalo, NY
University of California, Los Angeles, CA
California State University, Dominguez Hills, CA
Carnegie Mellon University, Pittsburgh, PA
Catholic University of America
CEA-Saclay, Gif-sur-Yvette, France
Christopher Newport University, Newport News, VA
University of Connecticut, Storrs, CT
Edinburgh University, Edinburgh, UK
Fairfield University, Fairfield, CT
Florida International University, Miami, FL
Florida State University, Tallahassee, FL
George Washington University, Washington, DC

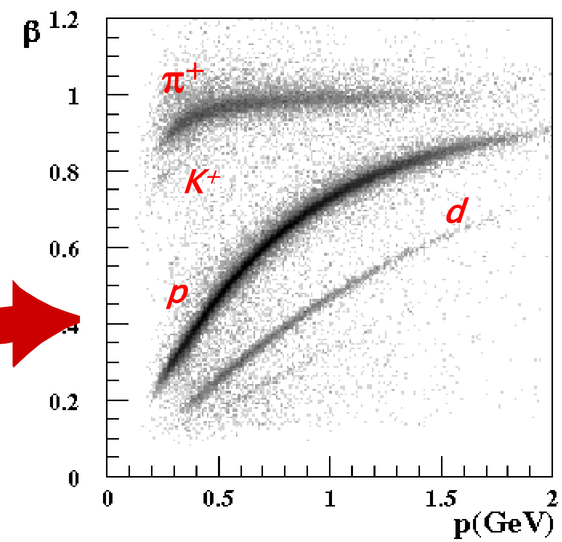
University of Glasgow, Glasgow, UK
Idaho State University, Pocatello, Idaho
INFN, Laboratori Nazionali di Frascati, Frascati, Italy
INFN, Sezione di Genova, Genova, Italy
INFN, Sezione di Roma Tor Vergata, Italy
Institut de Physique Nucléaire, Orsay, France
ITEP, Moscow, Russia
James Madison University, Harrisonburg, VA
Kyungpook University, Daegu, South Korea
LPSC, Grenoble, France
University of Massachusetts, Amherst, MA
Moscow State University, Moscow, Russia
University of New Hampshire, Durham, NH
Norfolk State University, Norfolk, VA
Ohio University, Athens, OH

Old Dominion University, Norfolk, VA
Rensselaer Polytechnic Institute, Troy, NY
Rice University, Houston, TX
University of Richmond, Richmond, VA
University of South Carolina, Columbia, SC
Thomas Jefferson National Accelerator Facility, Newport News, VA
Union College, Schenectady, NY
Virginia Polytechnic Institute, Blacksburg, VA
University of Virginia, Charlottesville, VA
College of William and Mary, Williamsburg, VA
Yerevan Institute of Physics, Yerevan, Armenia
Brazil, Germany, Morocco and Ukraine,
as well as other institutions in France and in the USA,
have individuals or groups involved with CLAS,
but with no formal collaboration at this stage.

Physics with CLAS



The Particle are identified speed



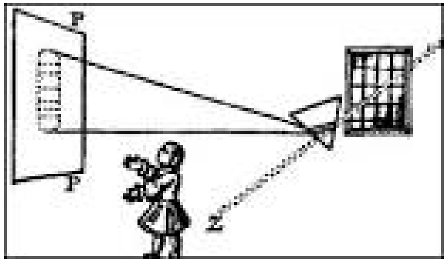
Spectrum of the hydrogen atom

- 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.

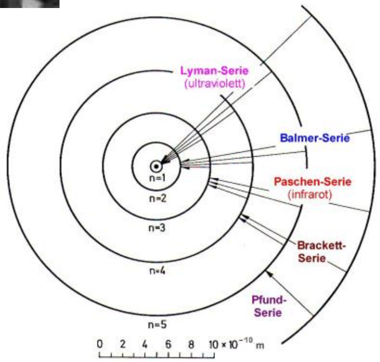
- Much of the structure of the proton is revealed by the excitation spectrum of its constituents.

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

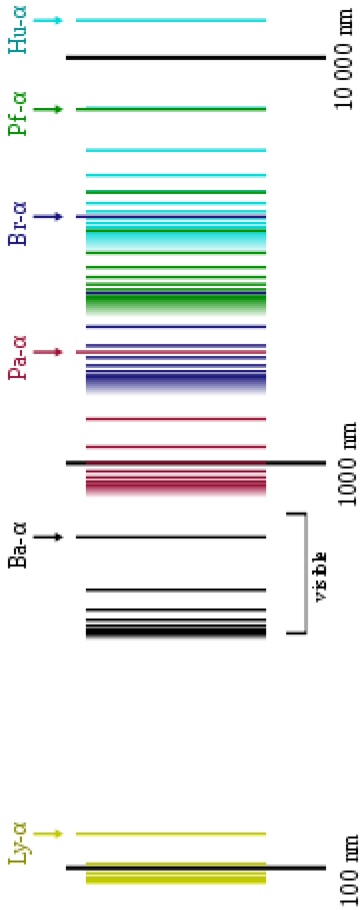
I. Newton, 1666



N. Bohr 1913

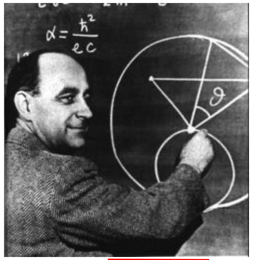


Spectral series of hydrogen, today



Jefferson Lab

First baryon resonance and beyond

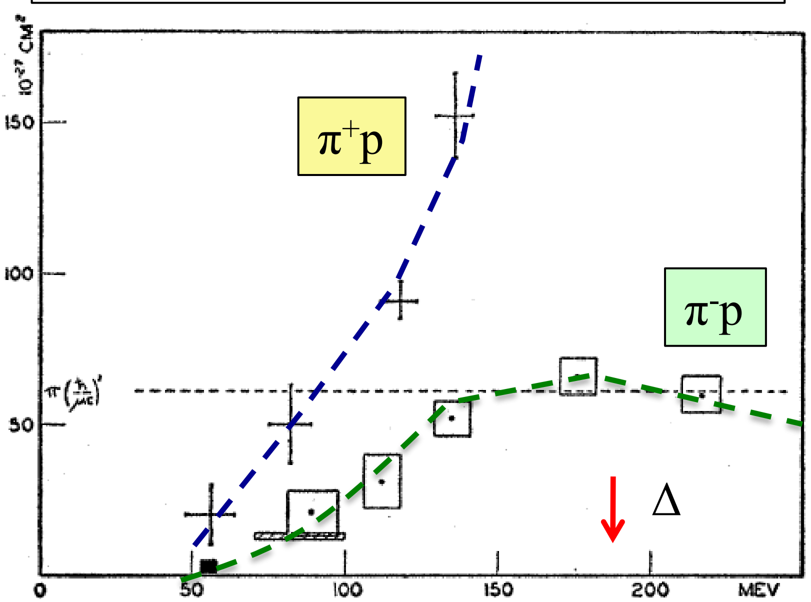


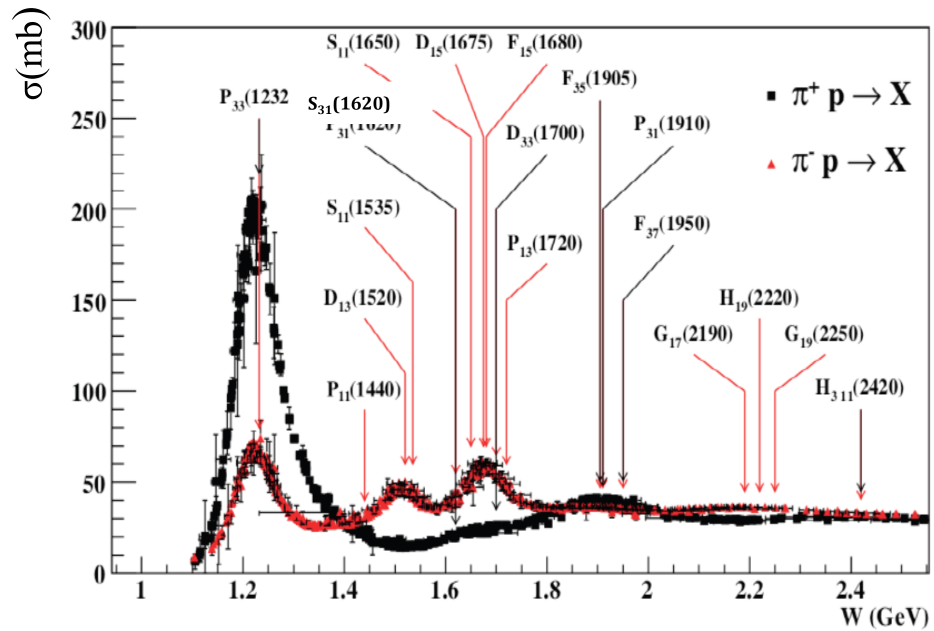
E. Fermi , 1952

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)

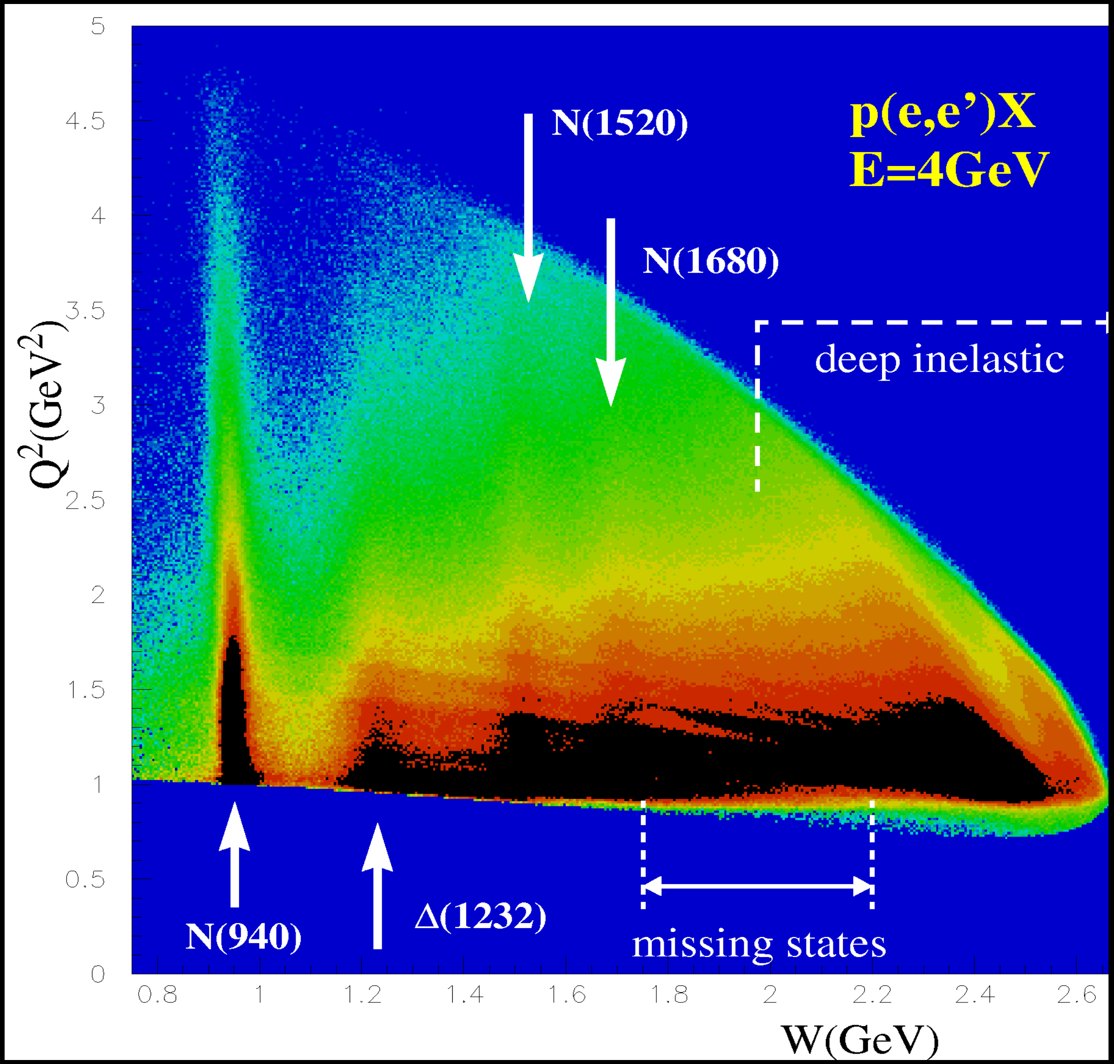




Many states discovered in pion-nucleon elastic scattering πN-->πN.

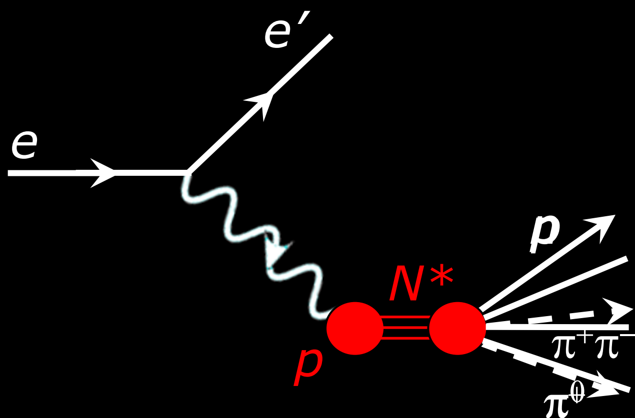
Many states expected from symmetric CQM were not found – have they escaped detection because they do not couple to πN?

Nucleon Excitation



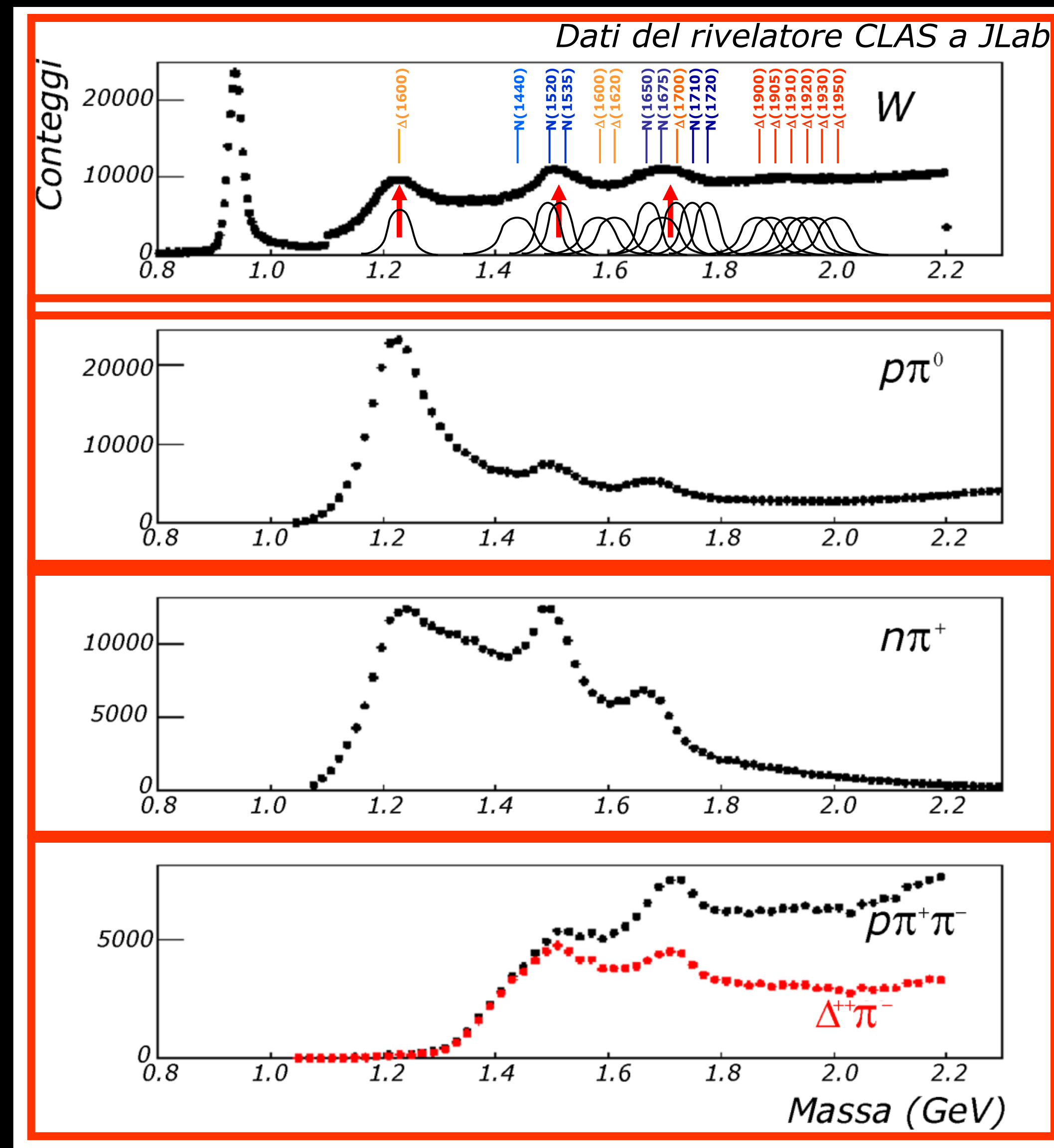
First experiments with CLAS

Nucleon excited states with the CLAS Detector



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

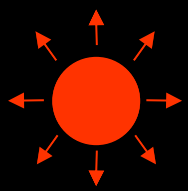
The measurement of the final states allows the separation of different resonances

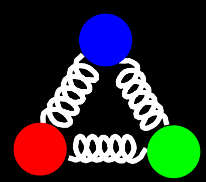


Roper resonance example nucleon excitation study with CLAS

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

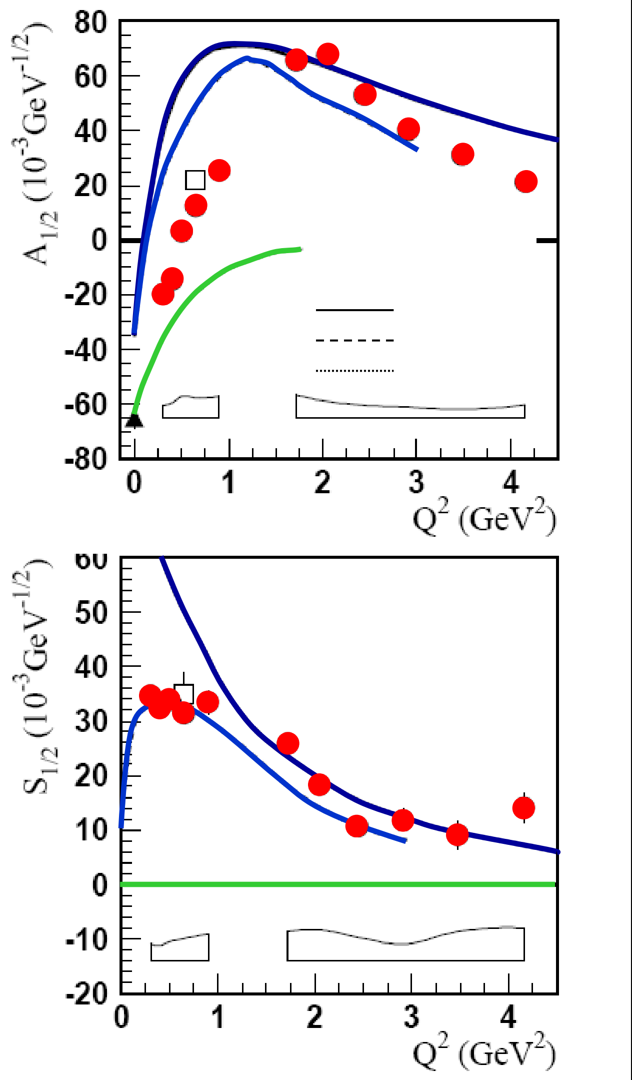
- is it due to the radial excitation of the nucleon?
- is it a hybrid state 3QG?





The data from CLAS at JLab have allowed for the **first time** 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)

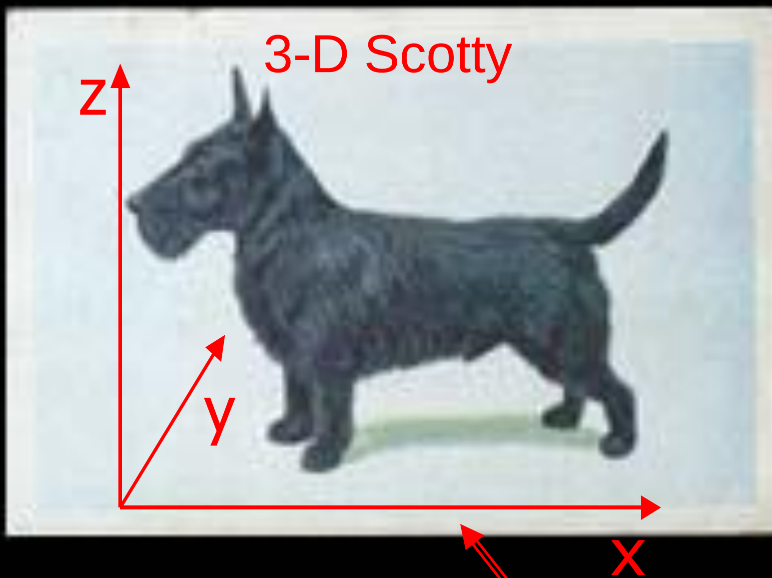
What are Generalized Parton Distributions ?

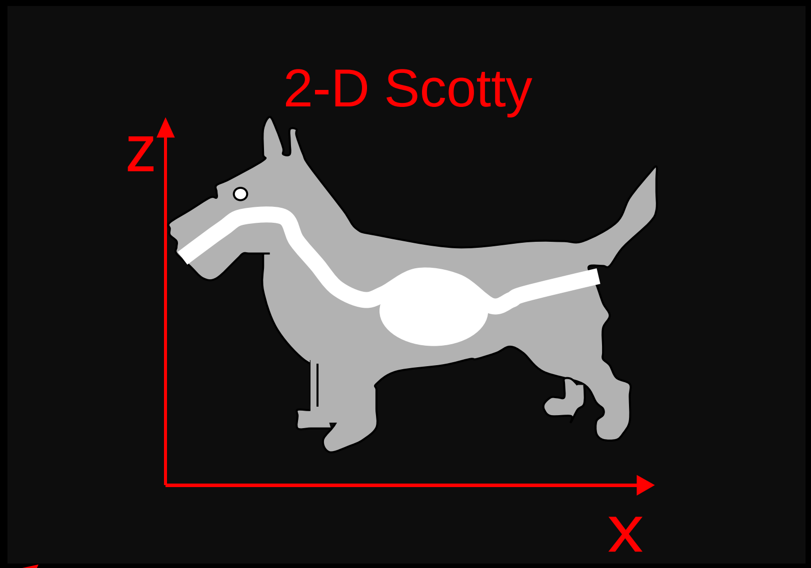
As Form Factors do, they contain information about the positions of quarks in the nucleon, like one obtains by taking a sharp picture

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

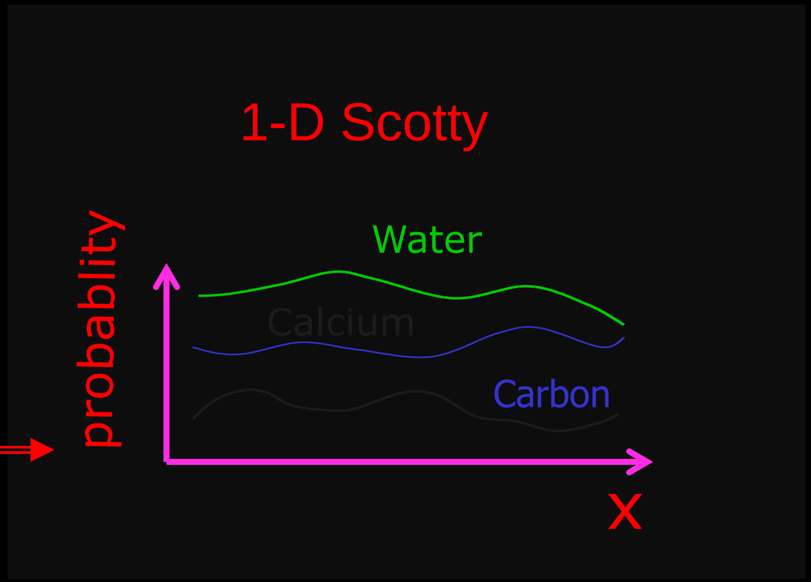
GPDs & PDs

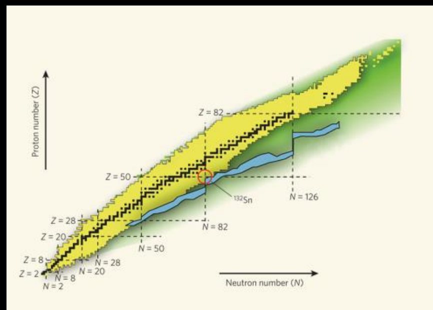




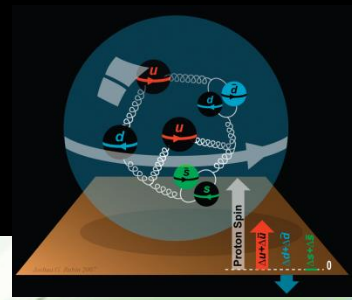
Deeply Virtual Exclusive Processes & GPDs

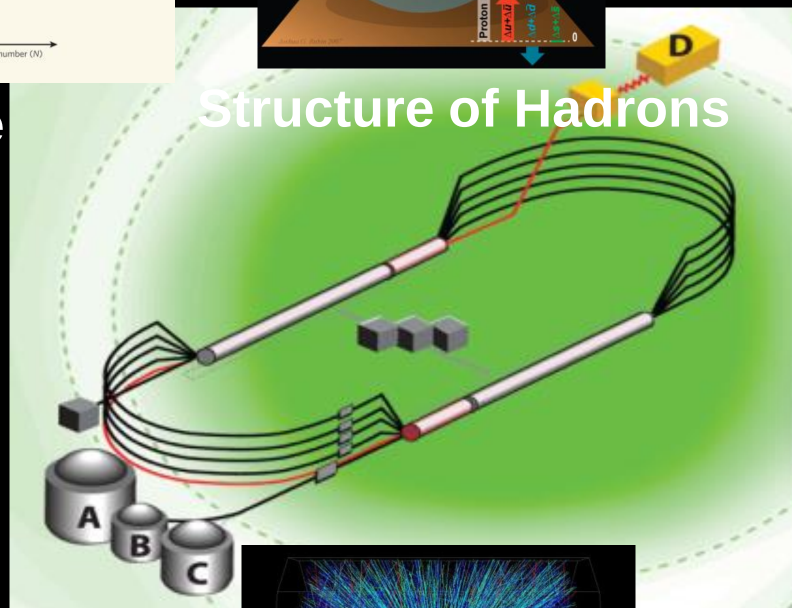
Deep Inelastic Scattering & PDs



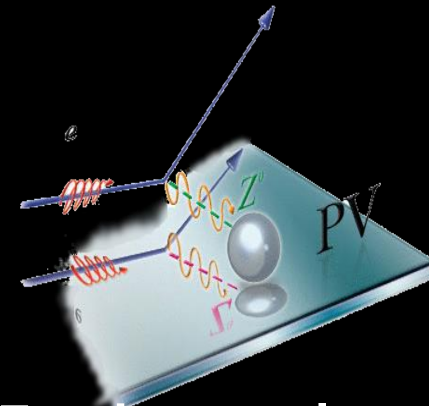


Nuclear Structure





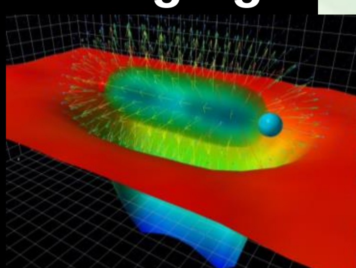
Structure of Hadrons



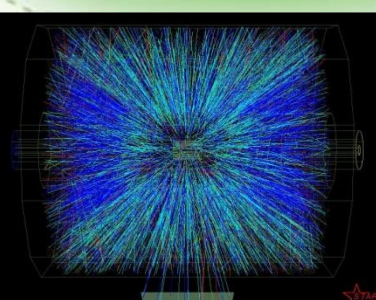
Fundamental Forces & Symmetries

Medical Imaging

Accelerator S&T

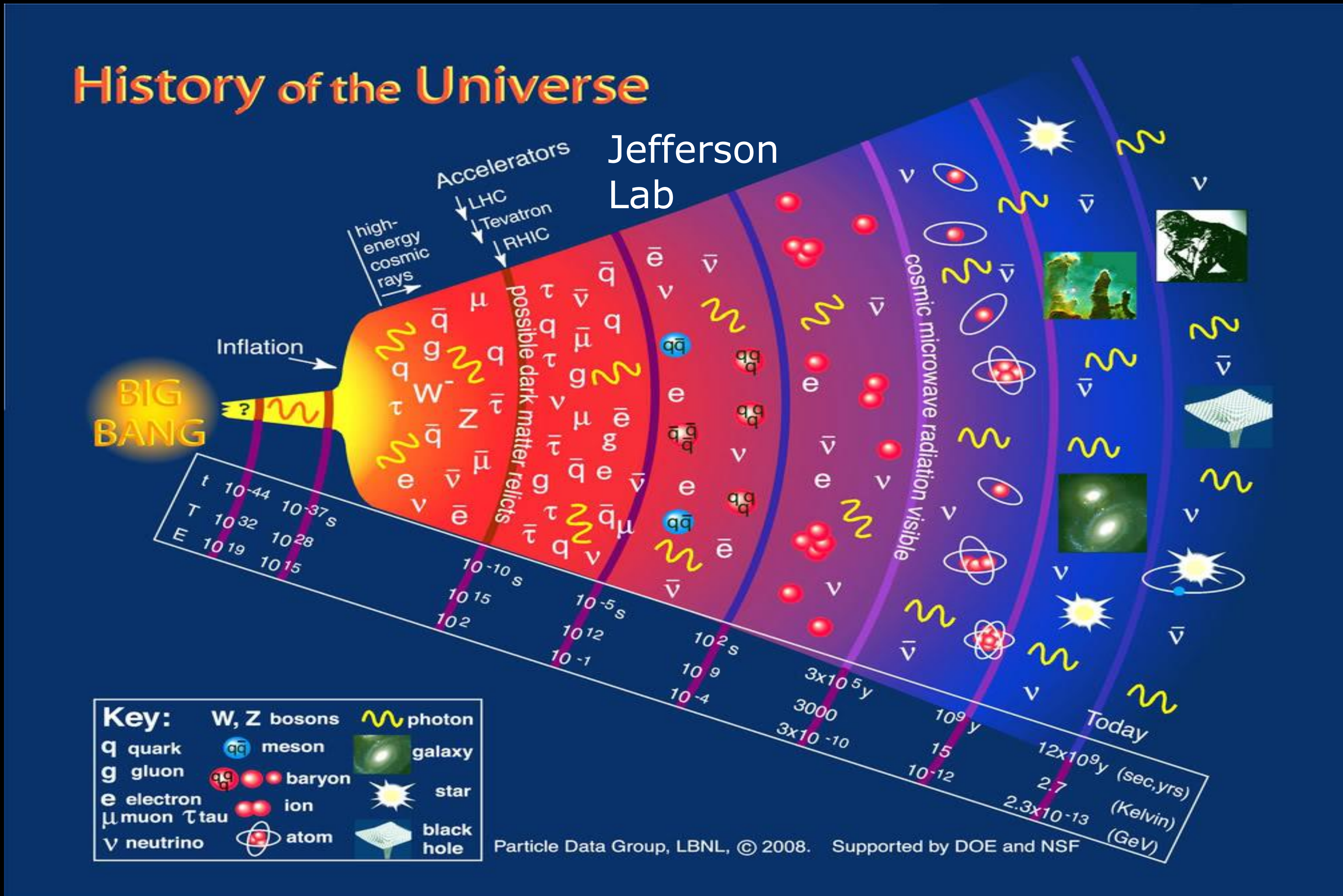


Quark Confinement



Hadrons from Quarks

Theory and Computation


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 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF