Rutherford's Legacy in Particle Physics: Exploring the Proton

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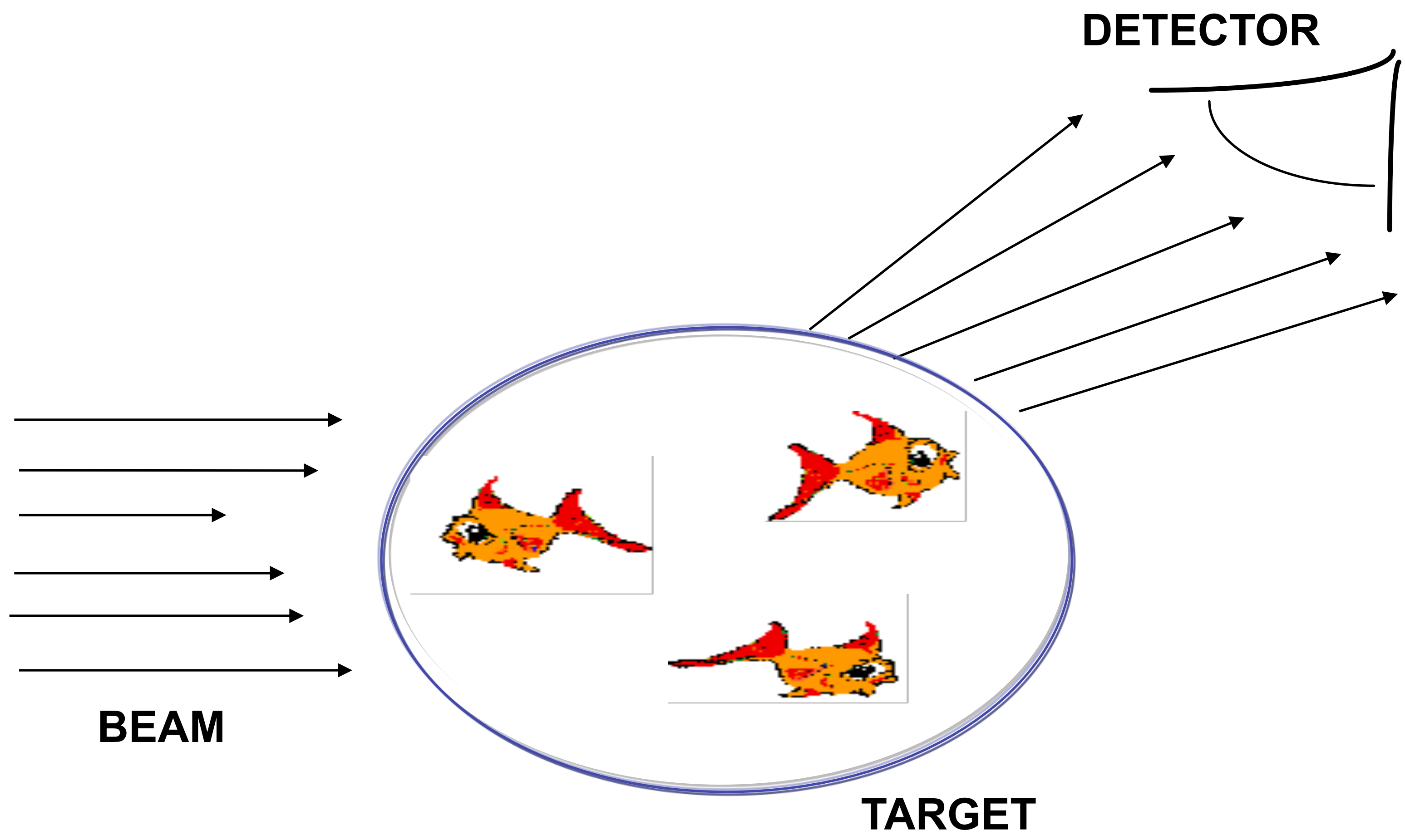
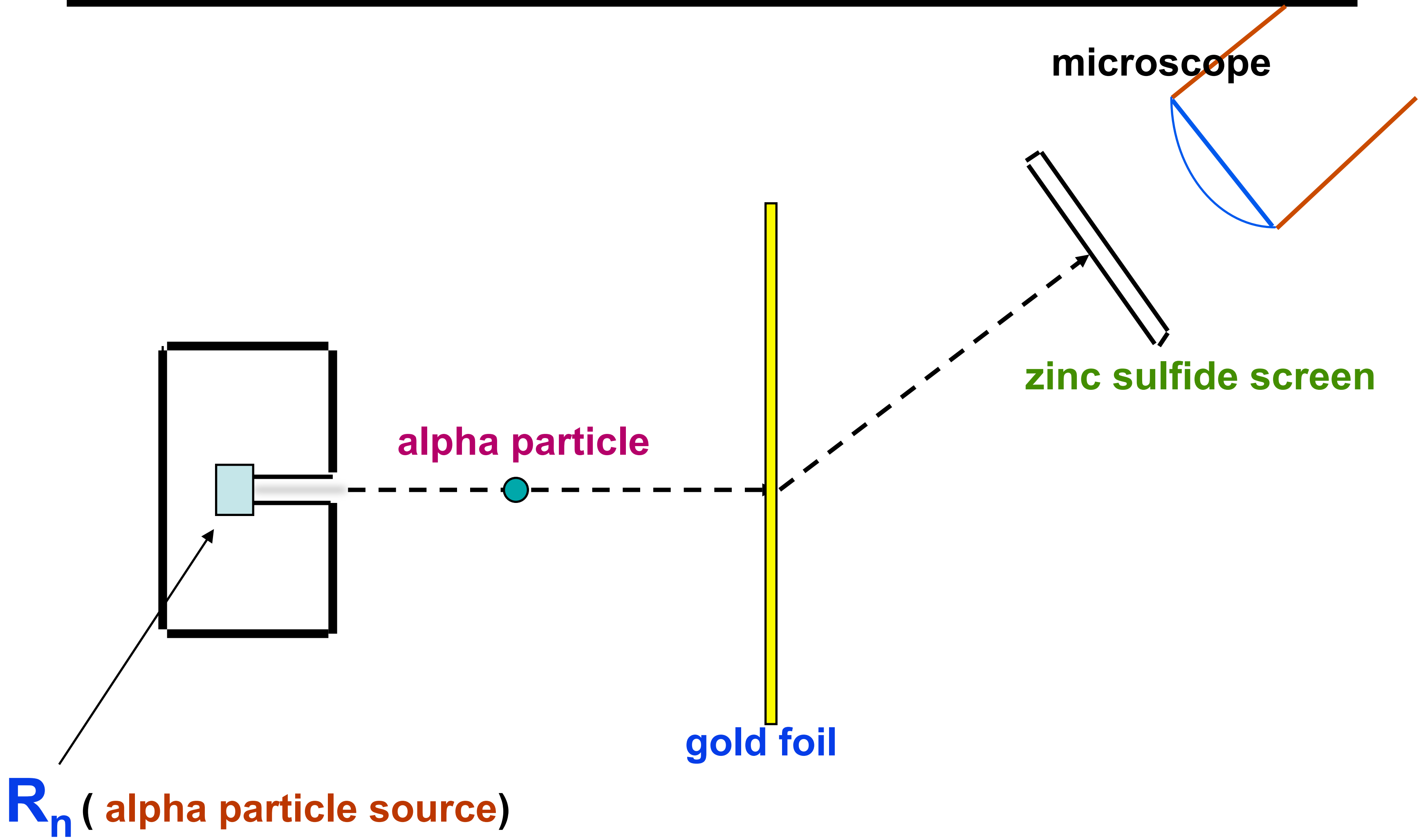
MIT

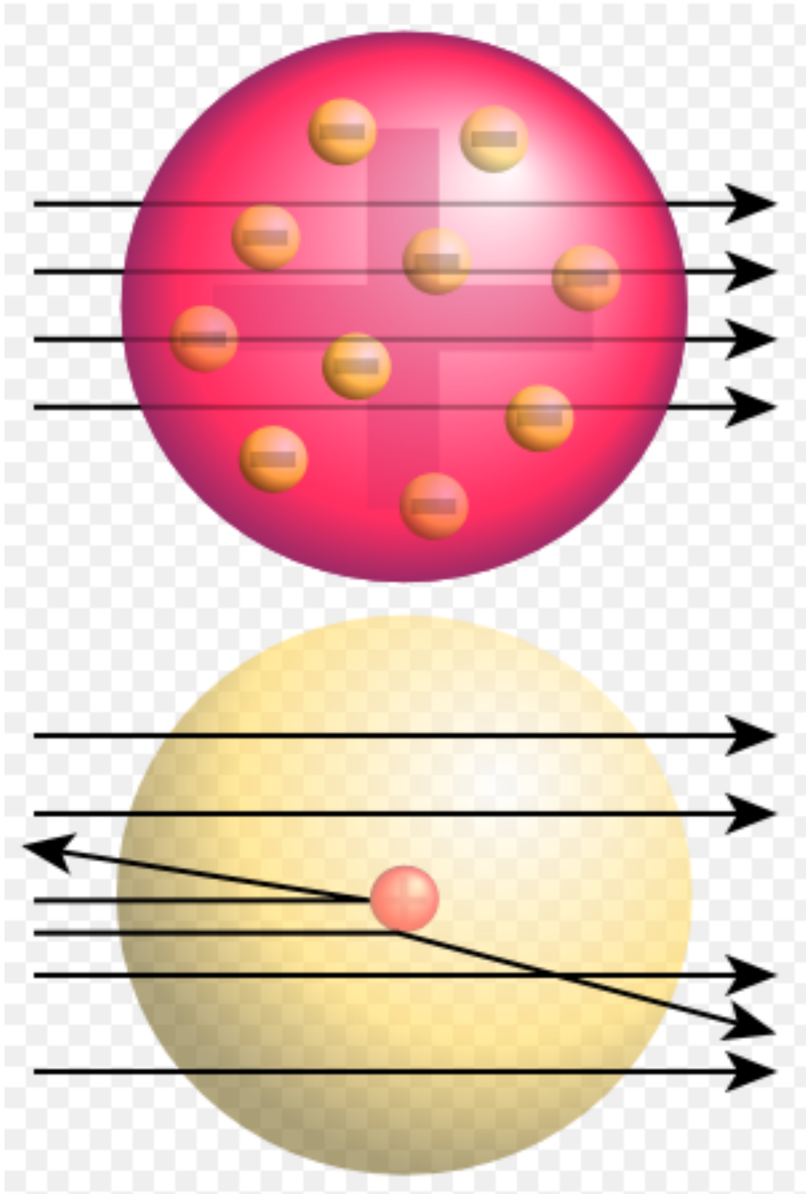
Scattering can determine structure: Rutherford's great legacy



Rutherford's Scattering Experiment - 1911



Confirmed "solar system" model : ATOMIC NUCLEUS DISCOVERED



Plum Pudding Model

J.J. Thomson

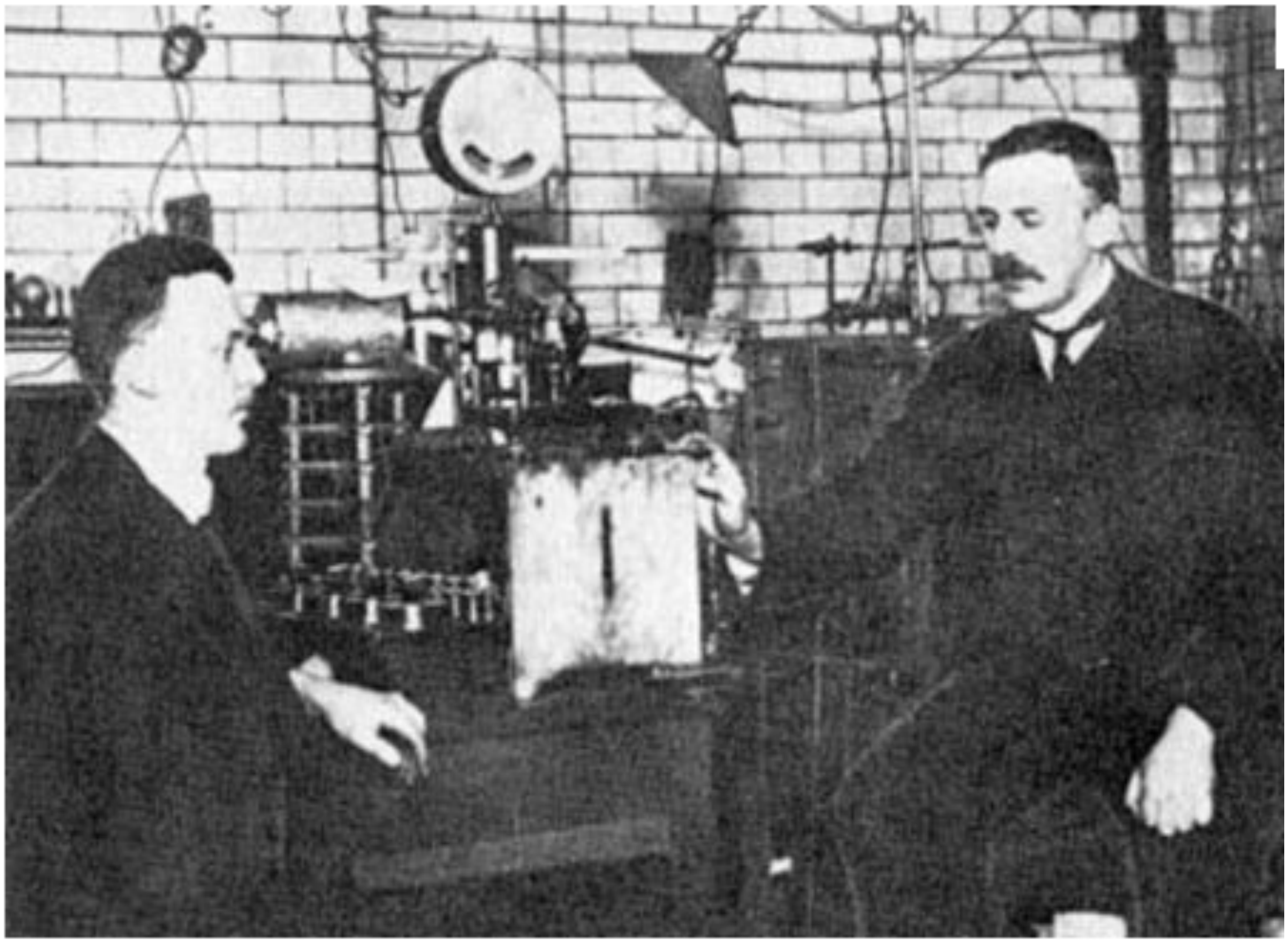
1904

Solar System Model

Hantaro Nagaoka

1904

Rutherford in His Laboratory

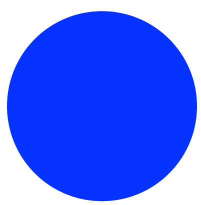


Higher Beam Energies Needed

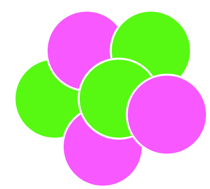
Higher energies provide higher magnifications and resolutions

$\lambda = h / p$

Accelerators are Powerful Microscopes.



seen with
low energy beam
(poorer resolution)

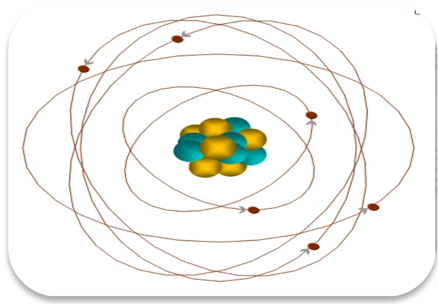


seen with
high energy beam
(better resolution)

Developing powerful accelerators, physicists have followed Rutherford's leg**a**cy to uncover structure of matter

Magnification
1

Bulk Matter

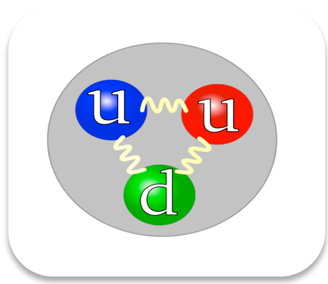


Magnification
100,000,000

Atom

Magnification
X 100,000

Nucleus



Magnification
X 10000

Quarks in Protons & Neutrons

Atomic Nucleus Discovered 1911

Constituents of Atomic Nucleus Uncovered 1919 - 1932

Proton Discovered in 1919
Neutron Discovered in 1932

In the late 1950's, the proton's RMS radius was found to be about 10^{-13} cm.

Are they Fundamental Particles ?

Prevailing model of the proton in the 1960's

All particles equally fundamental

NUCLEAR DEMOCRACY

BOOTSTRAP MODEL

Particles are composites of one another

$$p = \pi^{+} + n + \ldots\ldots$$

$$n = \pi^{-} + p + \ldots\ldots$$

Particles have diffuse substructures and no elementary building blocks

1964 **Gell-Mann & Zweig** proposed that protons and neutrons and other particles are composed of spin ½ constituents - QUARKS

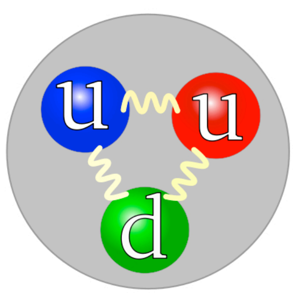
3 types

UP, DOWN, STRANGE

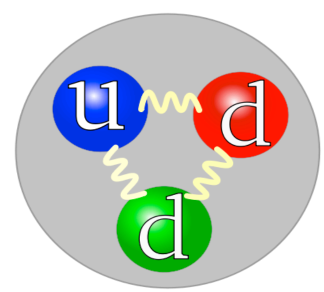
they have fractional charges

UP ***(+2/3)*** ***DOWN (-1/3)*** ***STRANGE (-1/3)***

proton = (u, u, d)



neutron =(d, d, u)



Are Quarks Real?

MANY UNSUCCESSFUL SEARCHES

- **Accelerators, Cosmic rays, Terrestrial environment Sea water, Meteorites, Air, etc.**

FRACTIONAL CHARGES

- **Considered by many to be unreasonable**

GENERAL POINT OF VIEW IN 1966

Quarks most likely just mathematical representations

***Useful but* NOT *real* !**

Particles have diffuse substructures and no elementary building blocks

Implausibility of Quark Model

" ...the idea that mesons and baryons are made primarily of quarks is hard to believe.."

M. Gell-Mann 1966

" Additional data are necessary and very welcome to destroy the picture of elementary constituents."

J. Bjorken 1967

" I think Professor Bjorken and I constructed the sum rules in the hope of destroying the quark model."

K. Gottfried 1967

" Of course the whole quark idea is ill founded."

J.J. Kokkedee 1969

Stanford Linear Accelerator (SLAC)

Completed in 1966

Inelastic e-p Scattering

Experiments 1967 - 1974

MIT - SLAC

e + p $\longrightarrow$ e + Many Particles

PROVIDED FIRST DIRECT EVIDENCE FOR QUARKS

MIT - SLAC Group

W.B. Atwood
E.D. Bloom
A. Bodek
M. Breidenbach
C. Buschhorn
R.L.A. Cottrell
D. Coward
H. DeStaebler
R. Ditzler
J. Drees
J. Elias
J.I. Friedman
G. Hartmann
C.L. Jordan
H.W. Kendall
M. Mestayer
G. Miller
L.Mo
H. Piel
J.S. Poucher
M. Riordan
D. Sherden
M. Sogard
S. Stein
R.E. Taylor
R. Verdier

Discovery of Quarks (1968 -1972)

MIT-SLAC

Experiments utilized the equivalent of a powerful ELECTRON MICROSCOPE.

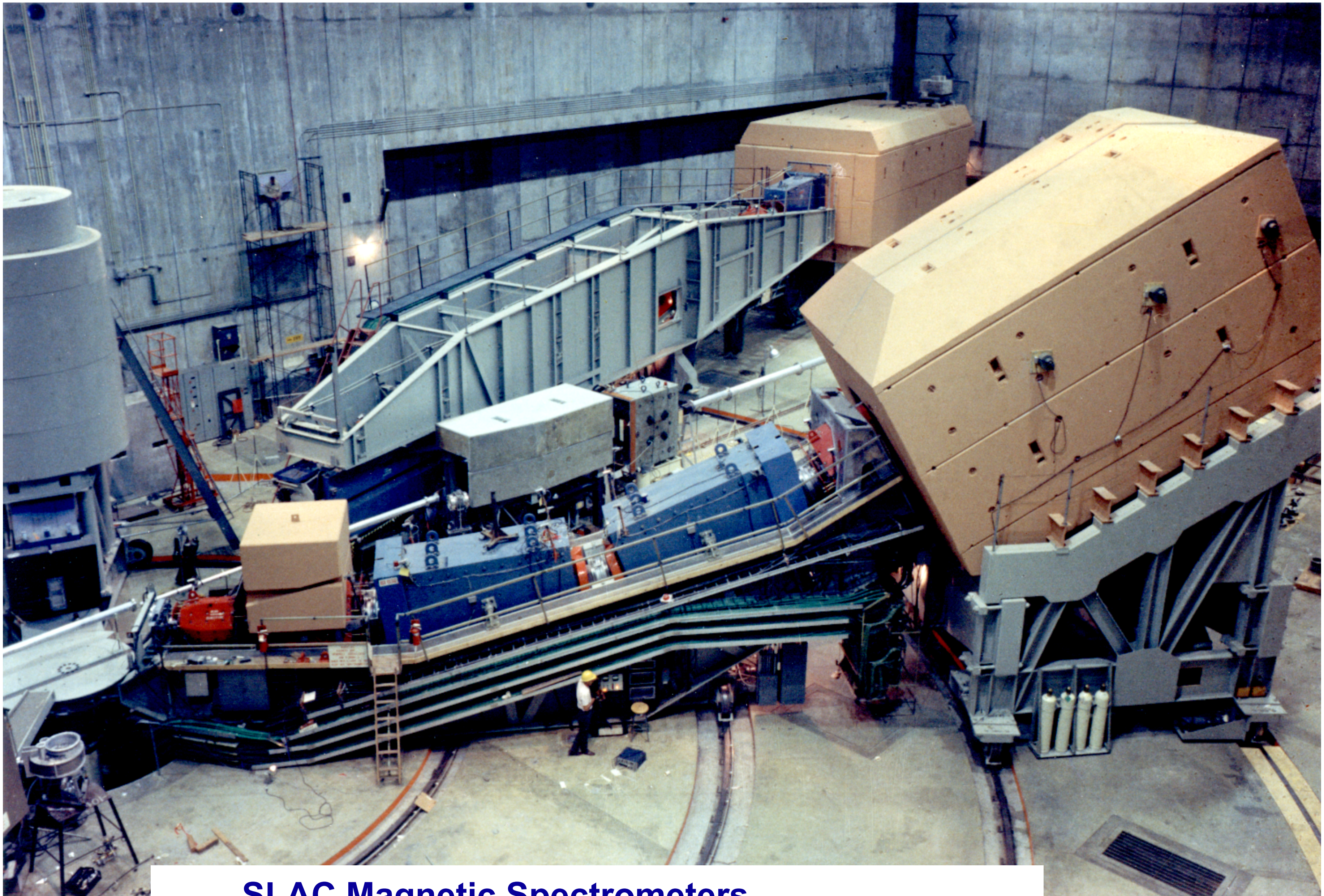
Examined the insides of the Proton and Neutron

Linear Accelerator (SLAC) provided 20 Billion electron-volt electrons.

Effective MAGNIFICATION was 60 Billion times greater than with ordinary light.

(Effective Magnification is proportional to Energy).

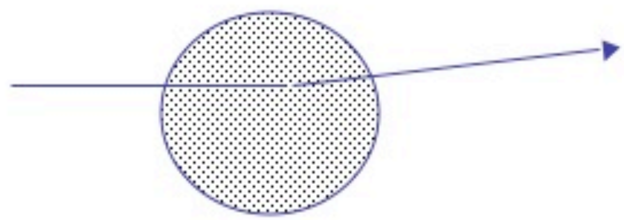
Stanford Linear Accelerator



SLAC Magnetic Spectrometers

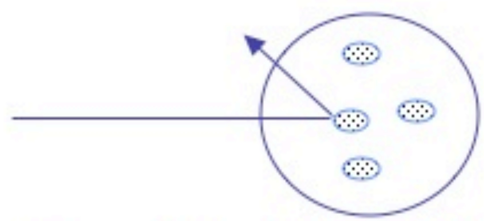
Scattering

From Diffuse Substructure

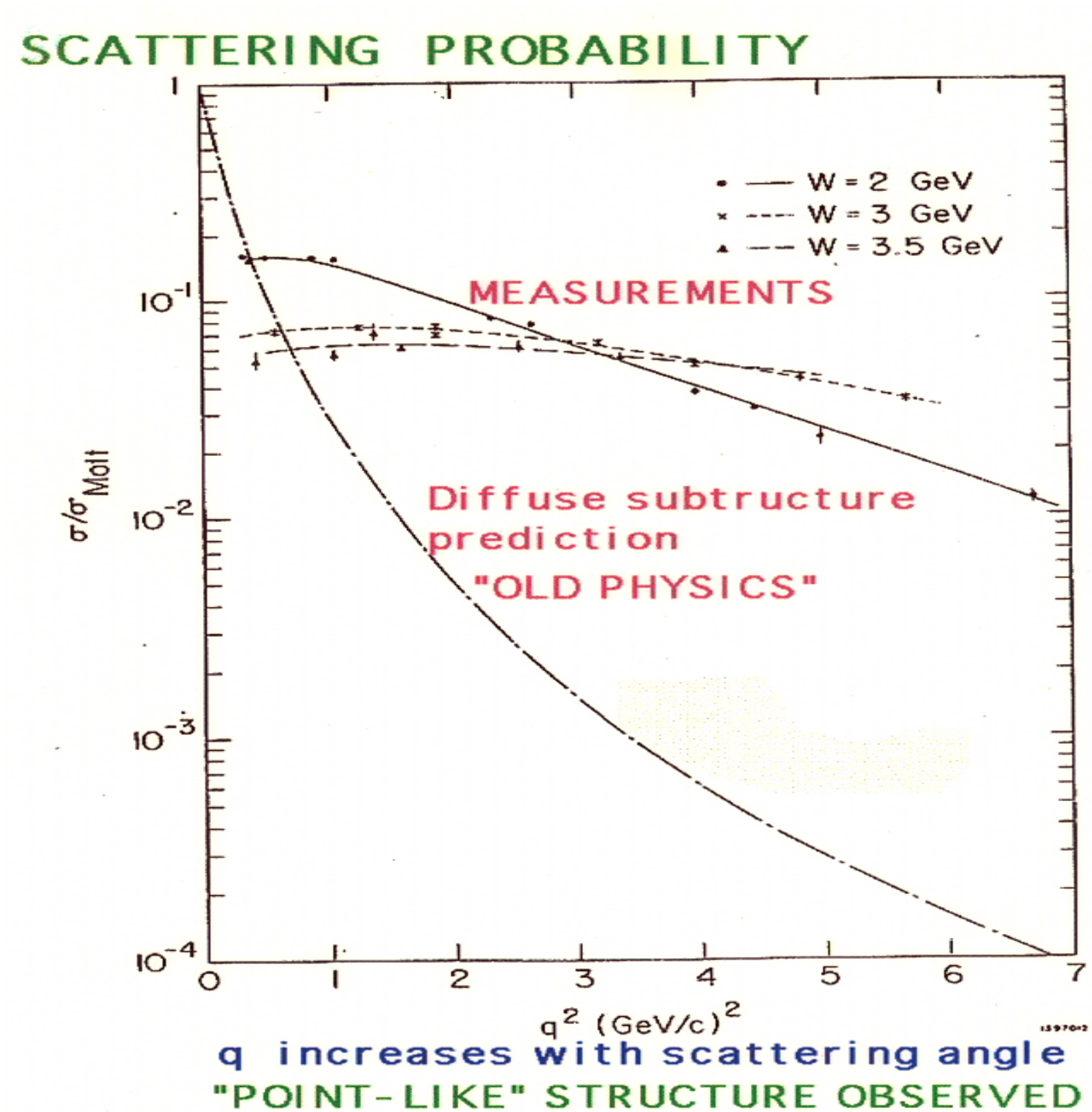


Model
of Proton
in 1960's

From Constituent Substructure



* Large Angle Scattering Implies
Smaller Objects Inside Particle



Results suggested that proton has "point-like" constituents

If Constituents are Quarks

1) They must be spin 1/2 particles

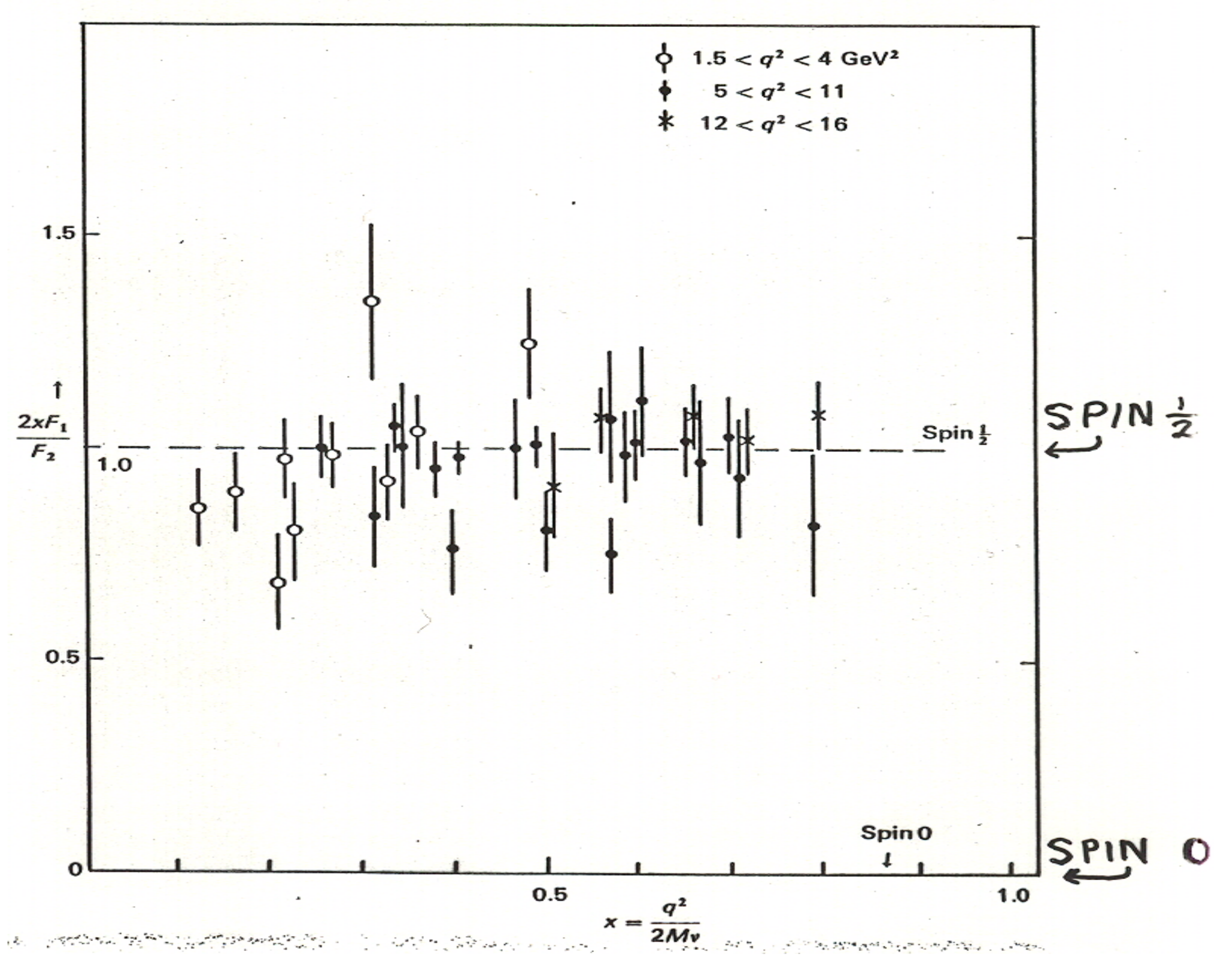
2) They must have fractional charges consistent with the quark model

Comparisons of forward and backward scattering answered the question:

What is the the spin of the constituents?

Spin 1/2

Spin 0



Do Constituents have Fractional Charges (+2/3, -1/3)?

- Comparisons of Electron Scattering and Neutrino Scattering provided the answer.

- First neutrino results came from Large Heavy Liquid Bubble Chamber "Gargamelle" (1971-1974)

Neutrinos

3 types

Very small masses 10^{-1} - 10^{-2} eV

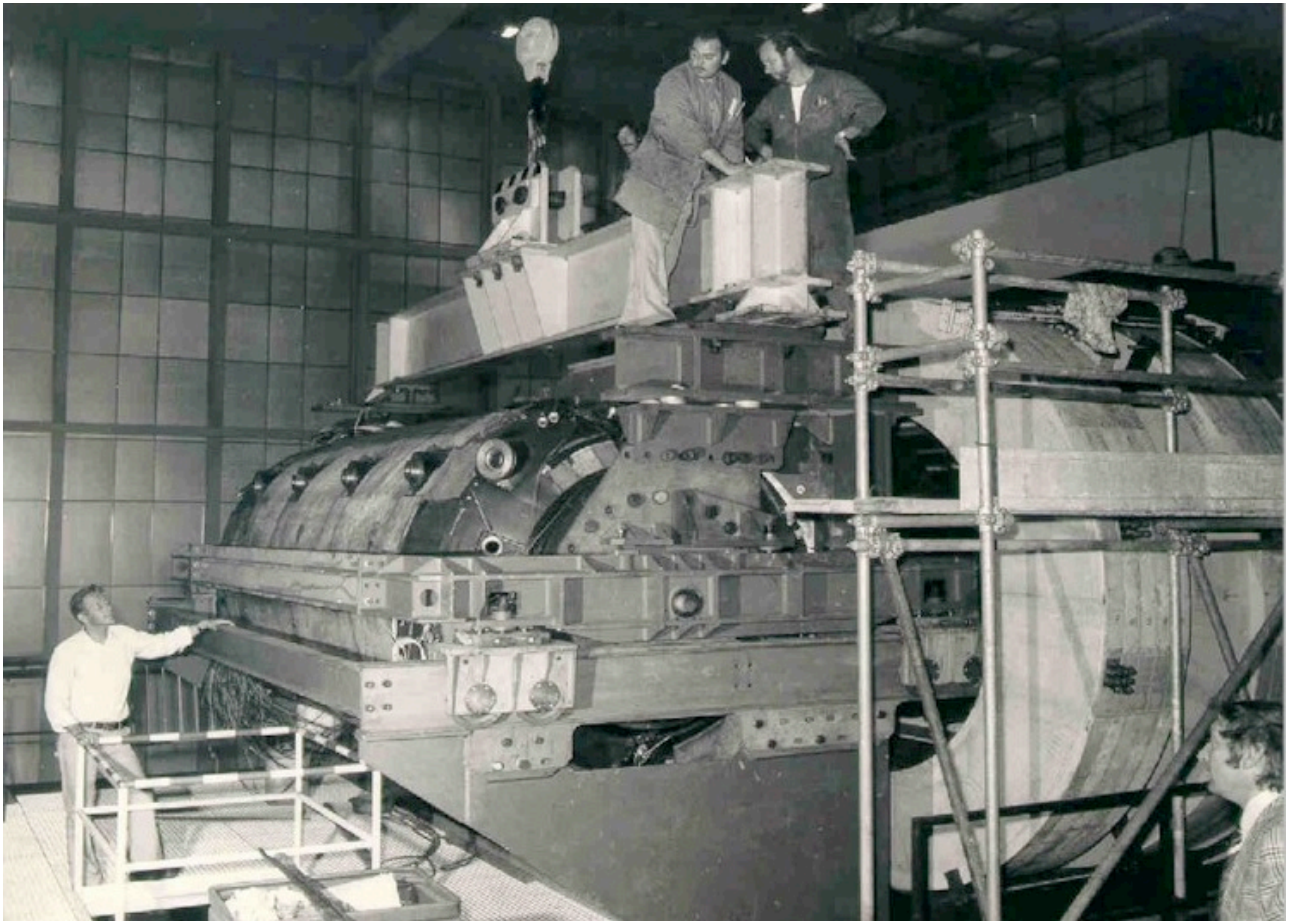
Charge = 0

Very small interaction probability:

A 100 Gev neutrino has a mean interaction length in iron of 2.5 MILLION MILES

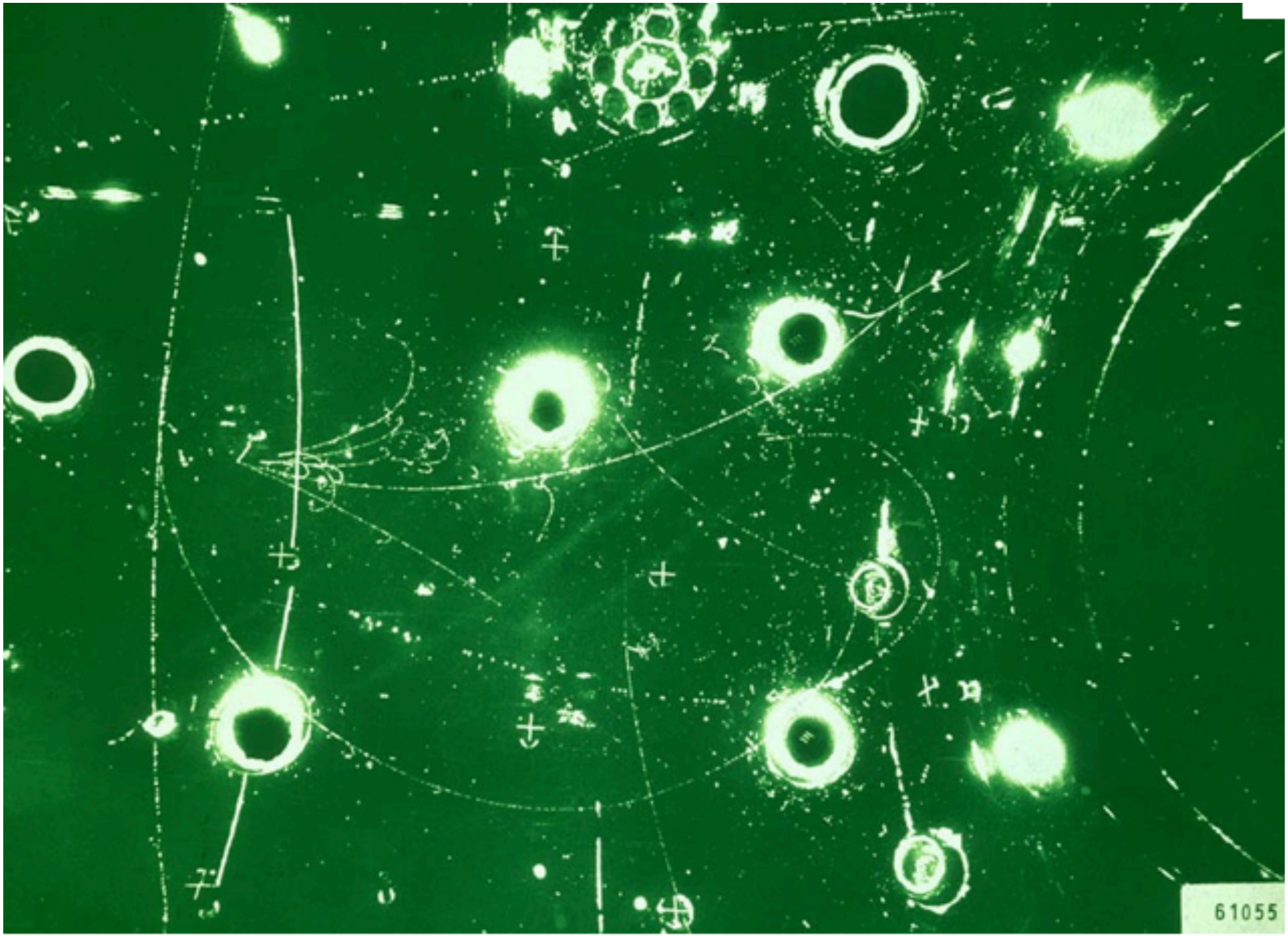
Neutrinos are produced in particle decays

GARGAMELLE



5 meters **12000 liters of Freon**

Neutrino Scattering Event in Gargamelle



COMPARISON OF ELECTRON AND NEUTRINO SCATTERING IN THE QUARK MODEL (1972-1974)

PREDICTED VALUE of

$$\frac{e^4 \text{ (probability of neutrino-scattering)}}{g^4 \text{ (probability of electron-scattering)}} =$$

$$= \frac{2}{(Q_u^2 + Q_d^2)}$$

$$= \frac{2}{(2/3)^2 + (1/3)^2}$$

$$= 3.6$$

EXPERIMENTAL VALUE (MIT-SLAC, CERN)

$$= 3.4 \pm 0.7$$

AGREEMENT WITH QUARK MODEL

Older models of particle structure were abandoned between 1972-1980

There have been a number of important experiments that provided further verification of the quark model and discovered new quarks.

Properties of Quarks

Flavor	u	d	s	c	b	t
Mass	**~ 2 MeV**	**~ 5 MeV**	**~100 MeV**	**~ 1.3 GeV**	**~ 4 GeV**	**173 GeV**
Charge	2/3	-1/3	-1/3	2/3	-1/3	2/3
Spin	1/2	1/2	1/2	1/2	1/2	1/2

SIZE OF QUARKS < 10^{-17} cm.

1973

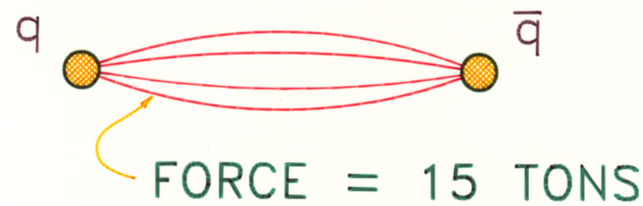
QCD Force approximately constant with increasing distance

– unlike Weak, EM and Gravitational Forces

ARE THERE FREE QUARKS?

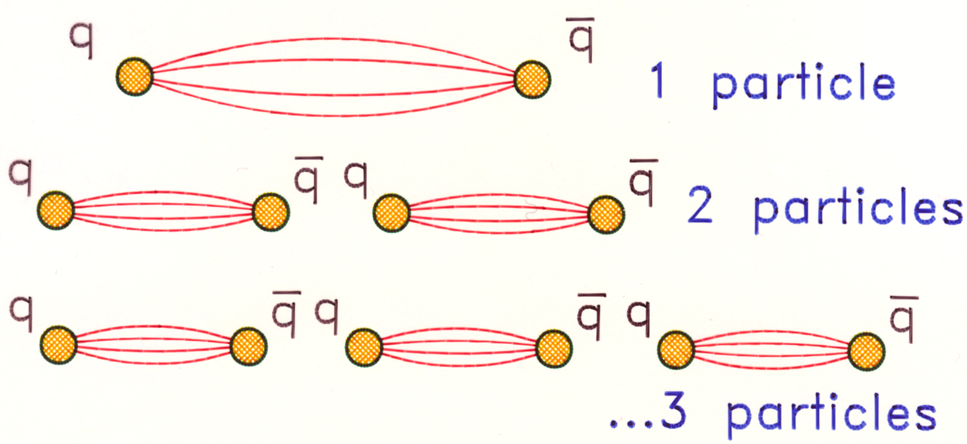
ACCORDING TO QUANTUM CHROMODYNAMICS, QUARKS ARE CONFINED.

Wilczek, Gross & Politzer



To separate 2 quarks by 1 CM requires energy of 10^{13} GeV

Long before this -- particles are produced



New Paradigm of the Structure of Matter

HOW "SOLID" IS MATTER ?

Consider the Carbon Atom

It Consists of 6e, 6p, 6n

or 6 electrons and 36 quarks

$R_{e,q} < 10^{-17}$ cm. $R_{carbon} \approx 10^{-8}$ cm.

$$\frac{\text{Volume of Quarks and Electrons}}{\text{Volume of Carbon Atom}} < 3 \times 10^{-25}$$

<3/10,000,000,000,000,000,000,000,00

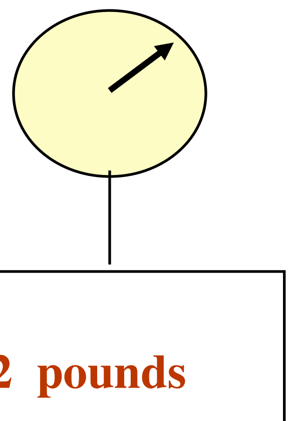
WHAT ABOUT MASS ?

Consider a 150 pound individual:

At fundamental level we all consist of ***u, d, e***

We know the masses of ***u, d, e***

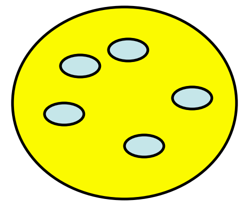
What is the total weight of all of the up quarks, down quarks and electrons in this individual?



$E = mc^2$

E (quark motion) + E (Force field) → 148 lbs.

Are there more fundamental particles inside of Quarks?

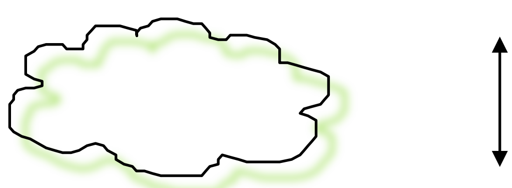


We don't know - but it is not ruled out by anything we know.

Quantum theory **tells us that such new particle would be confined by forces that are extremely strong:**

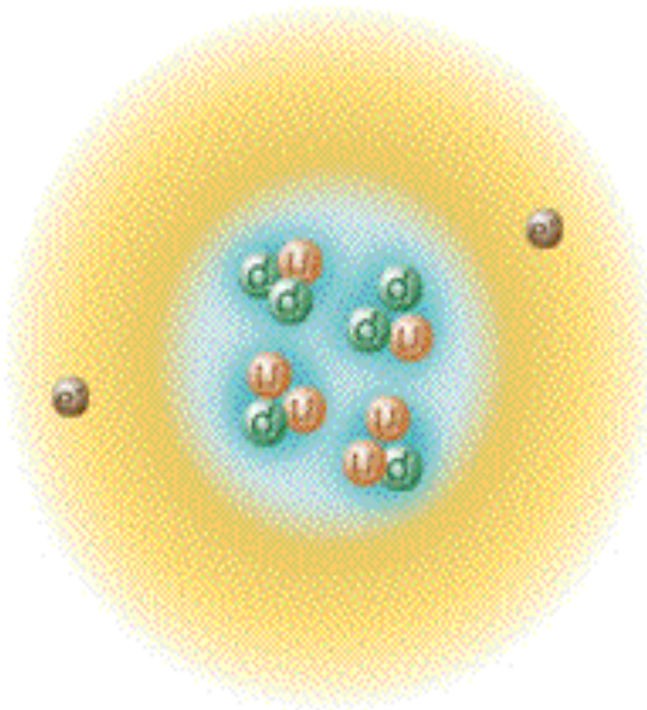
More than 100 million times stronger than the strongest forces we know!

Super String Theory **suggests that the fundamental building blocks are vibrating strings**



$\sim 10^{-32}$ cm.

What is ordinary matter made of?

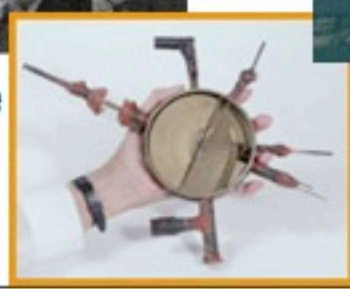


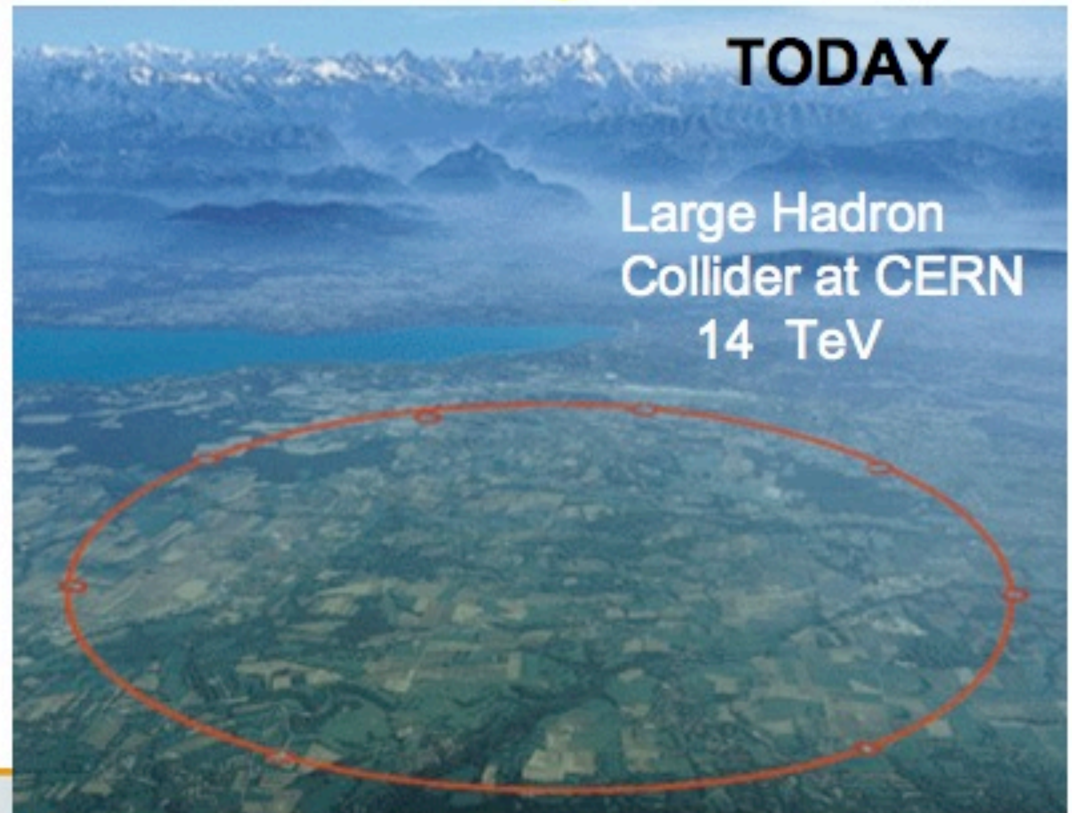
Size of electrons, up quarks and down quarks
$< 10^{-19}$ m = 0.0000000000000000001 m

Are they the smallest things? - LHC will probe this
Increasing magnification by about factor of 10

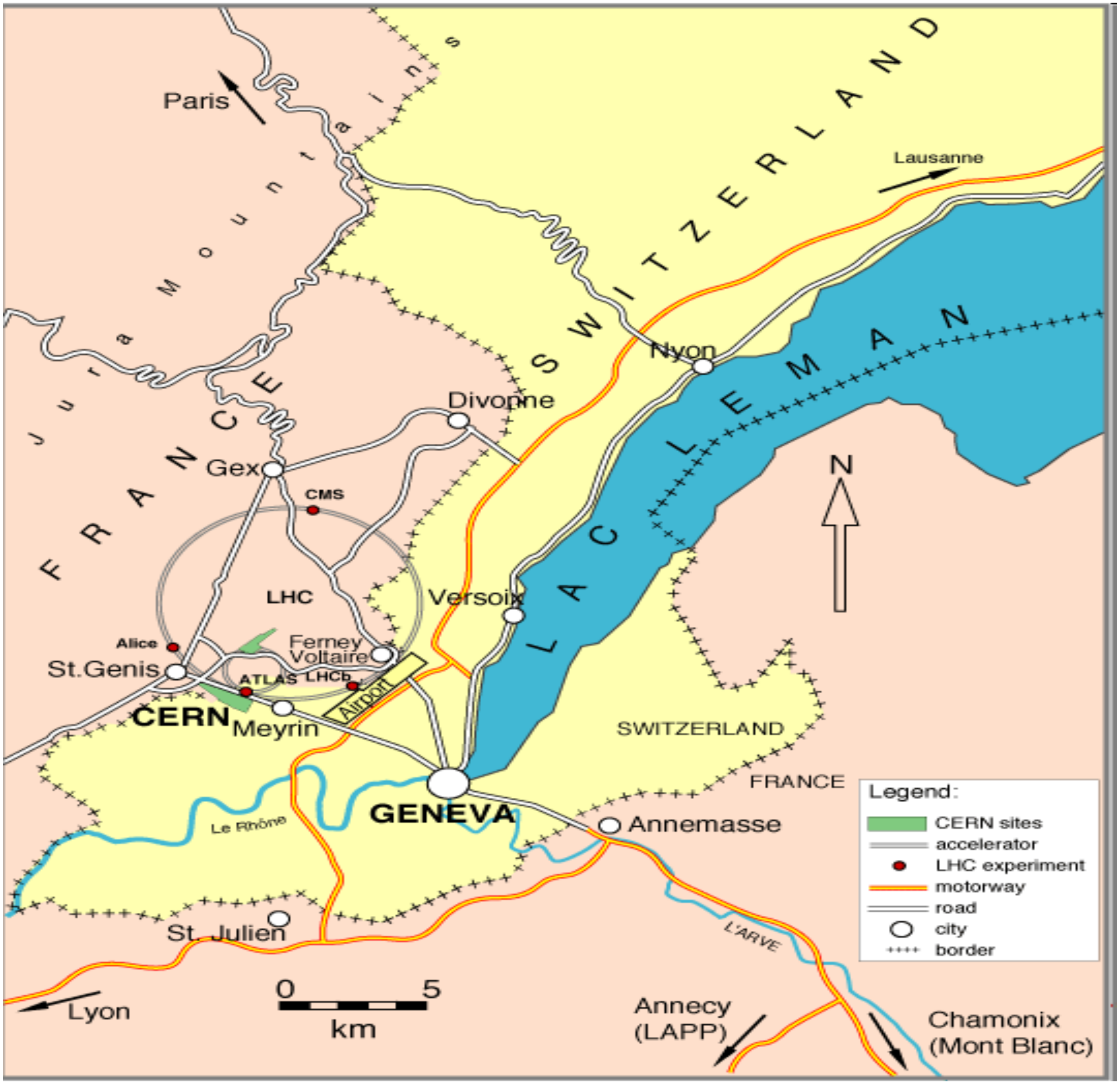
Many generations of Accelerators created with higher and higher energies given to the beam particles

Ernest Lawrence
(1901 - 1958)





27 km in circumference
10^7 higher energy

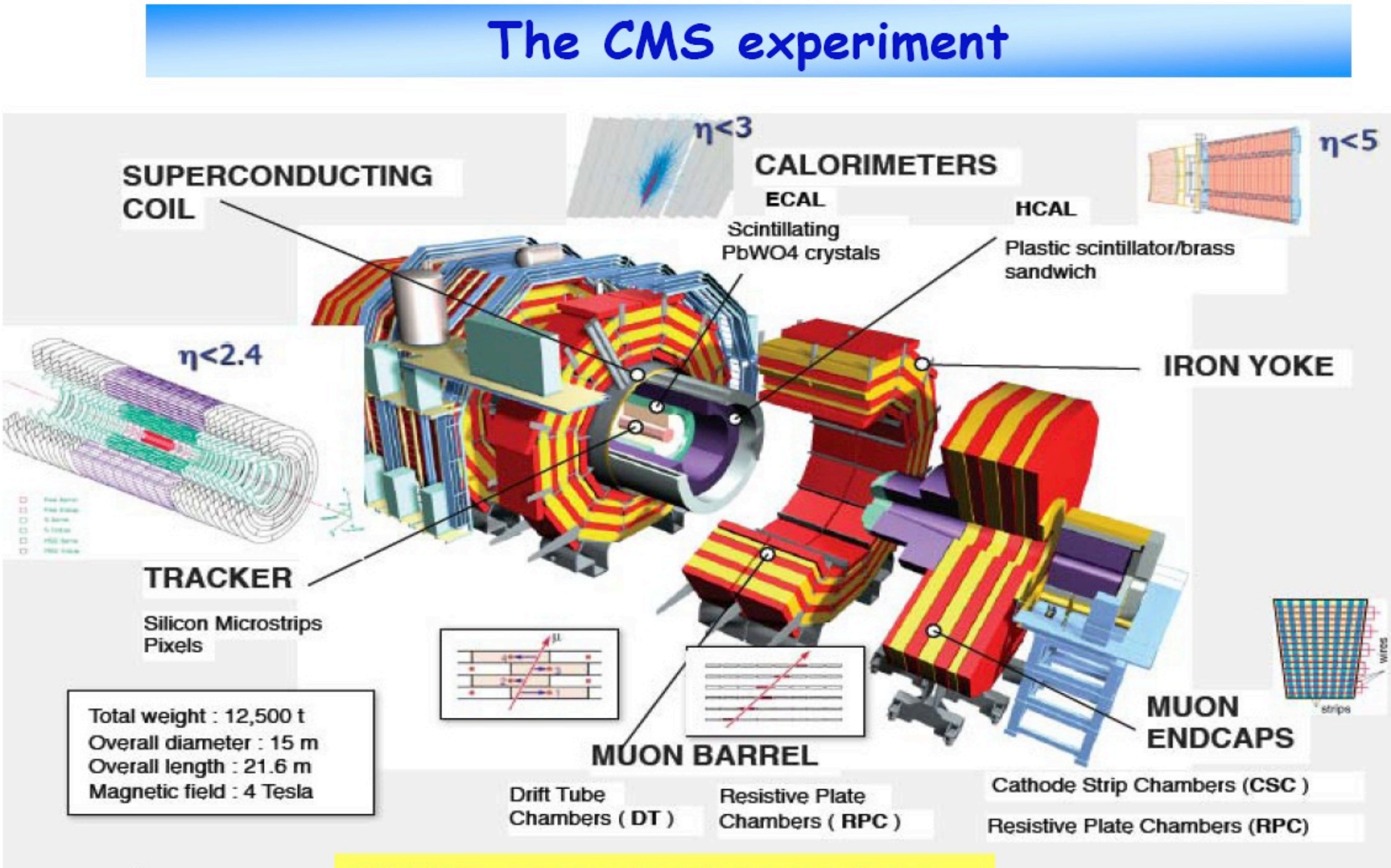


Paris
Jura Mountains
SWITZERLAND
Lausanne
Nyon
Divonne
FRANCE
Gex
CMS
LHC
Versoix
LAC LEMAN
N
Alice
Ferney Voltaire
St.Genis
ATLAS
LHCb
Airport
CERN
Meyrin
SWITZERLAND
FRANCE
GENEVA
Le Rhône
Annemasse
Legend:
CERN sites
accelerator
LHC experiment
motorway
road
city
border
St. Julien
L'ARVE
0
5
km
Lyon
Annecy
(LAPP)
Chamonix
(Mont Blanc)

LHC Tunnel

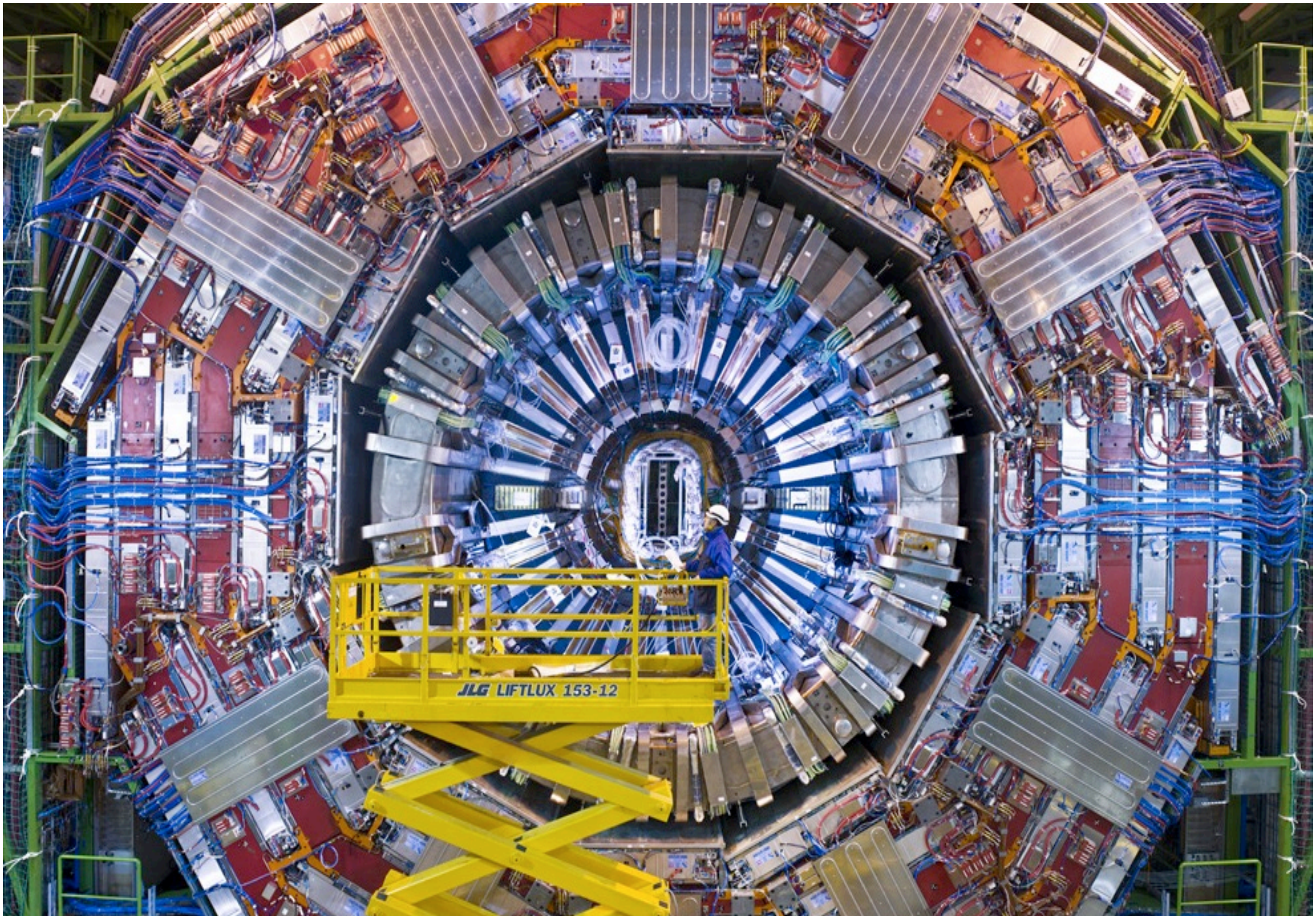
View of the LHC cryo-magnet inside the tunnel. (Maximilien Brice, © CERN)

LHC DETECTOR



CMS is assembled on surface

CMS

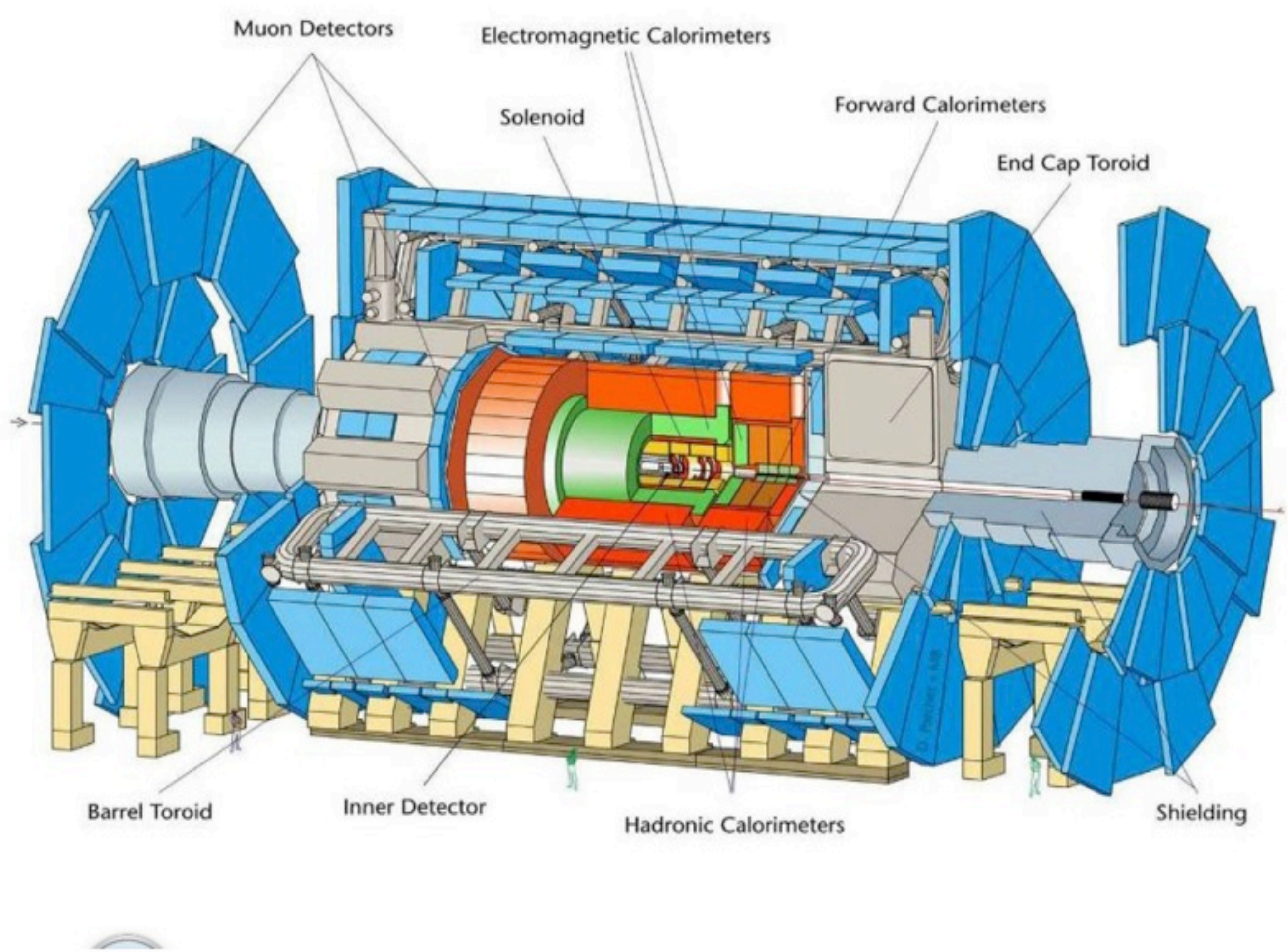


View of the CMS detector at the end of 2007. (Maximilien Brice, © CERN)

LHC DETECTOR

ATLAS

25 Meter Diameter
46 Meters Long



ATLAS

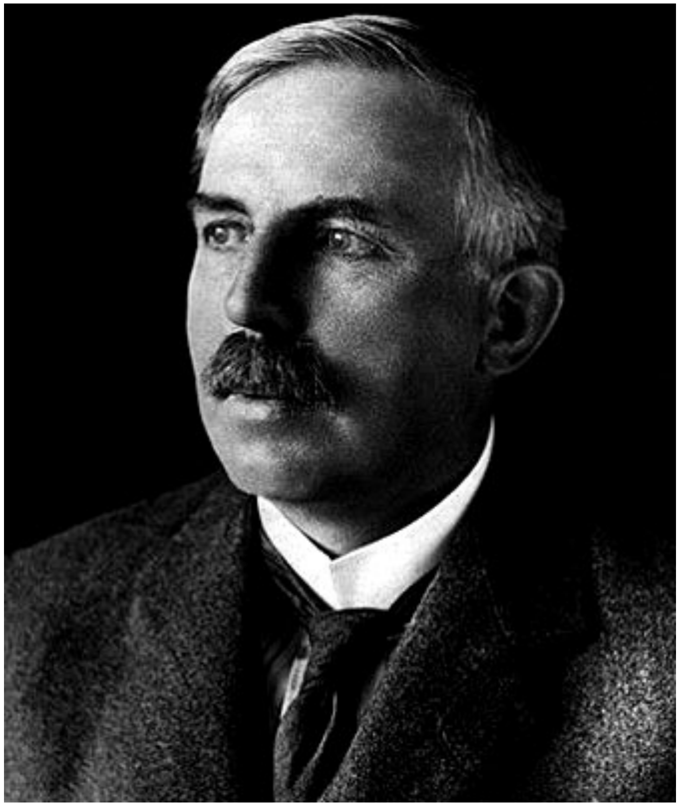
Installation of the Beam Pipe in the ATLAS cavern (Maximilien Brice, © CERN)

Rutherford's Legacy Continues:

The Large Hadron Collider will address a number of deep questions

- **Are quarks and electrons the smallest building blocks of matter?**
- **Are there new particles, new fields, new laws of physics?**
- **Are there extra dimensions of space?**
- **What happened to antimatter ?**
- **…………………**
  AND THERE WILL ALSO BE TOTALLY UNEXPECTED DISCOVERIES

The LHC will bring in a New Era of Discovery



In addition to his seminal discoveries, Rutherford has provided a legacy that has advanced nuclear and particle physics and continues to uncover the structure of matter