The scientific journey to Higgs boson … Not all roads lead to Rome, some lead to Geneva

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CERN, ROHSSIP, June 2024

-in Rom-lish

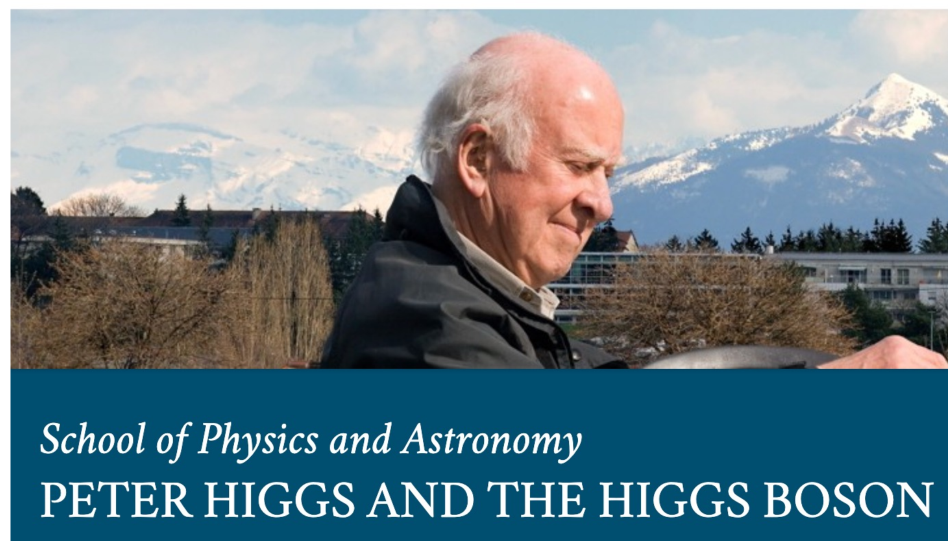
CERN, LHC experiment, 4 July 2012, ATLAS and CMS discovery of ~126GeV Higgs-like boson

What is mass? ... Massless particles?

Francois Englert

Robert Brout

THE UNIVERSITY *of* EDINBURGH



BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

Recently a number of people have discussed the Goldstone theorem [1,2]: that any solution of a Lorentz-invariant theory which violates an internal symmetry operation of that theory must contain a massless scalar particle. Klein and Lee [3] showed that this theorem does not necessarily apply in non-relativistic theories and implied that their considerations would apply equally well to Lorentz-invariant field theories. Gilbert [4], however, gave a proof that the failure of the Goldstone theorem in the nonrelativistic case is of a type which cannot exist when Lorentz invariance is imposed on a theory. The purpose of this note is to show that Gilbert's argument fails for an important class of field theories, that in which the conserved currents are coupled to gauge fields.

Following the procedure used by Gilbert [4], let us consider a theory of two hermitian scalar fields

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.[3] In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.[4-6] A

those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5-phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case that the pseudovector field acquires mass.

In the last paragraph we sketch a simple argument which renders these results reason-

1964theory

…48 years

2012 exp

By 1970s, physicists realised that two of the four fundamental forces—the weak force and the electromagnetic force—are very closely related. The two forces can be described within the same theory, which forms the basis of the Standard Model. This “unification” implies that electricity, magnetism, light, and some types of radioactivity are all manifestations of a single underlying force known as the electroweak force. The basic equations of the unified theory correctly describe the electroweak force and its associated force-carrying particles, namely the photon, and the W and Z bosons, except for a major glitch. All of these particles emerge without a mass. While this is true for the photon, we know that the W and Z have mass, nearly 100 times that of a proton. Fortunately, theorists Robert Brout, François Englert and Peter Higgs made a proposal that was to solve this problem. What we now call the Brout-Englert-Higgs mechanism gives a mass to the W and Z when they interact with an invisible field, now called the “Higgs field”.

Just after the Big Bang, the Higgs field was zero, but as the universe cooled and the temperature fell below a critical value, the field grew spontaneously so that any particle interacting with it acquired a mass. The more a particle interacts with this field, the heavier it is. Particles like the photon that do not interact with it are left with no mass at all. Like all fundamental fields, the Higgs field has an associated particle – the Higgs boson. The Higgs boson is the visible manifestation of the Higgs field.

Four fundamental forces

Electromagnetic force

Weak force

Electroweak force/field

Standard Model

Proton

Gauge theory

W and Z bosons

Higgs field

...

How many languages do you speak?

https://home.cern/science/physics/origins-brout-englert-higgs-mechanism

… But how did we get here?

- What are the fundamental constituents of the universe?
- What are we made of?
- How do they interact with each other?
- …

How to Judge What Physicists are Doing ?

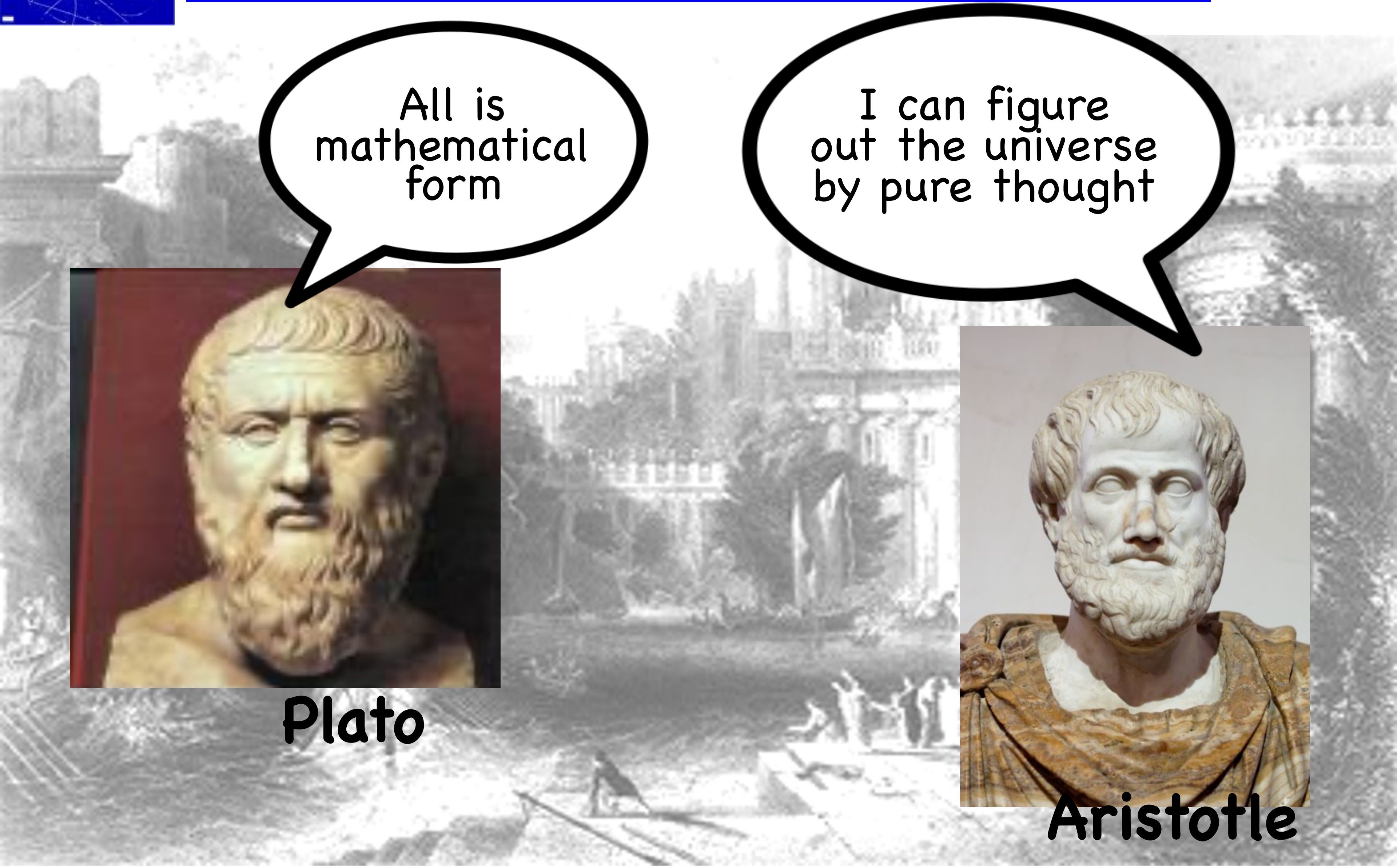
Constituents

- Number: economical
- Properties: few and simple
- Point-like? (no structure)

Theory

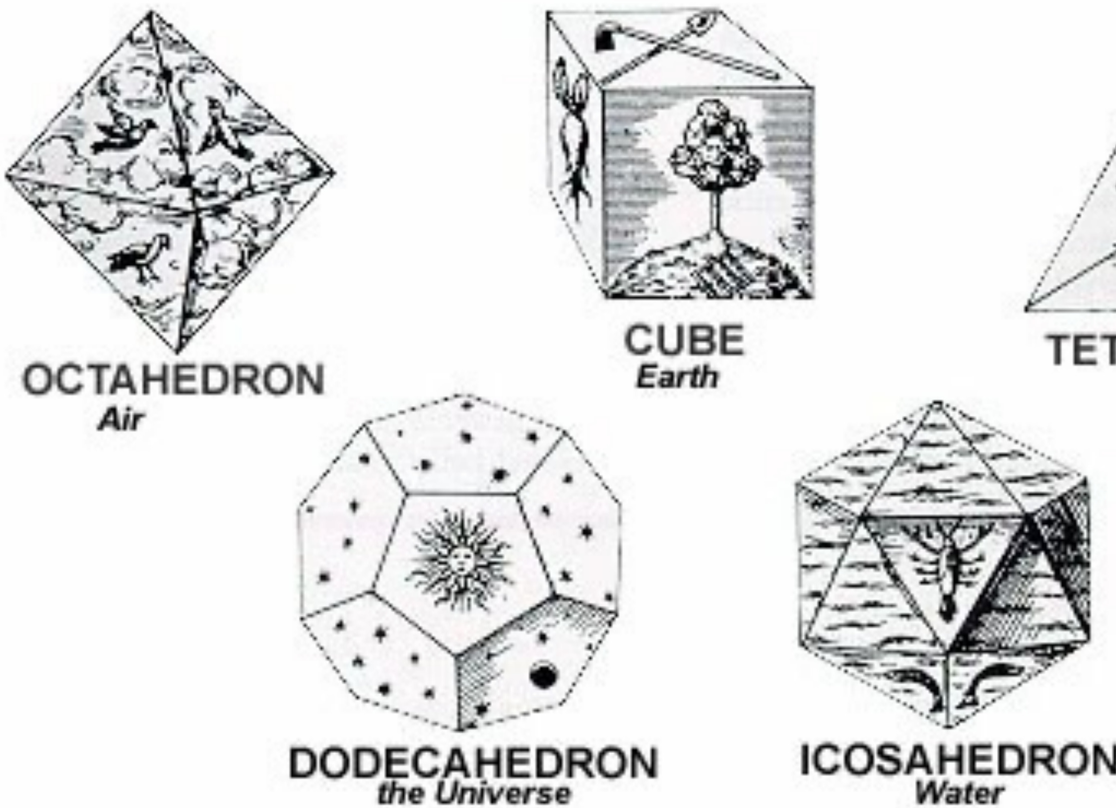
- Mathematically **consistent**
- **Explains** all observations
- Able to make **predictions**

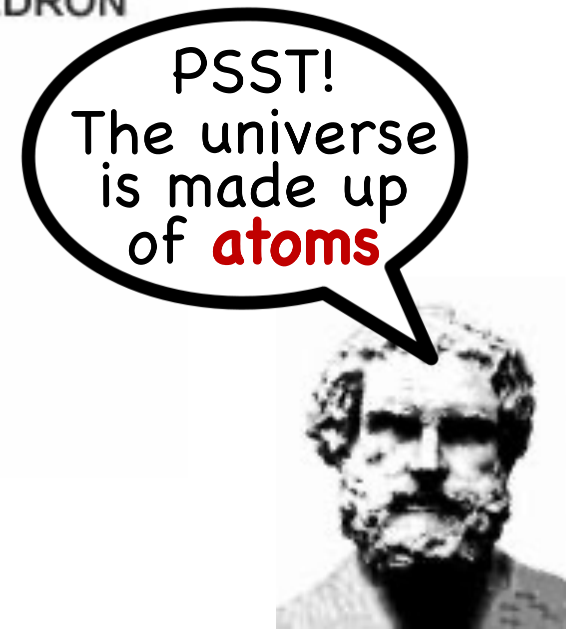
Ancient Greece



Fundamental Physics

Circa 500 B.C.





Democritus

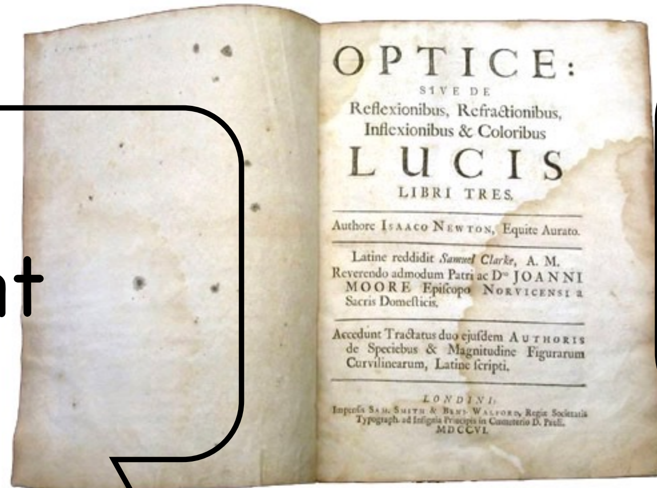
The universe is built on the five Platonic solids

The “Classical” Period

~1687 – ~1897

Newton

The world is made of point particles.



OPTICE:
SIVE DE
Reflexionibus, Refractionibus,
Inflexionibus & Coloribus
LUCIS
LIBRI TRES.

Authore ISAACO NEWTON, Equite Aurato.

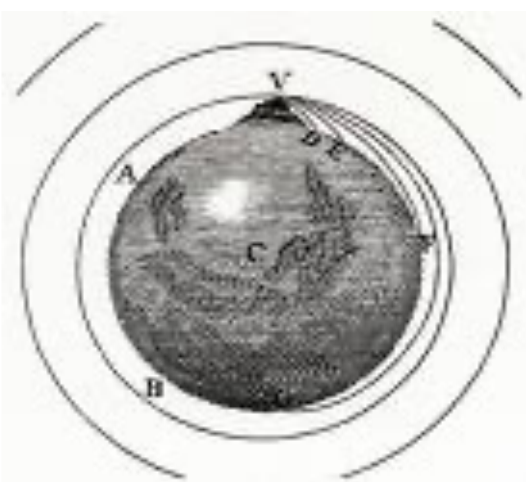
Latine reddidit Samuel Clarke, A. M.
Reverendo admodum Patri ac D^no JOANNI MOORE Episcopo NORVICENSI a Sacris Domesticis.

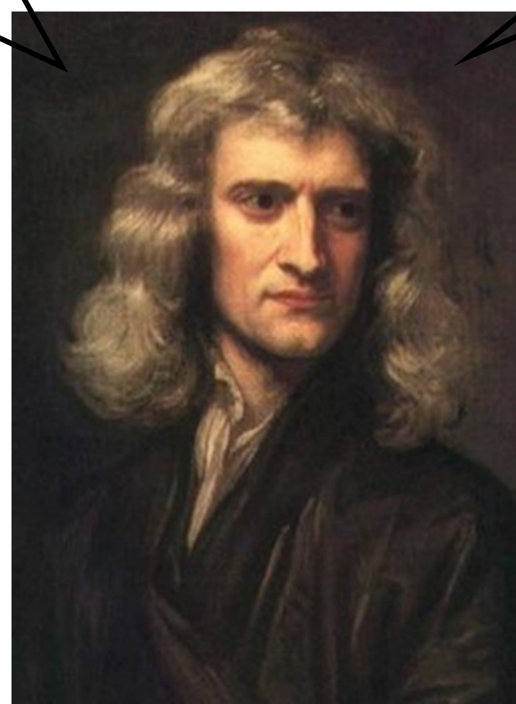
Accedunt Tractatus duo ejusdem AUTHORIS de Speciebus & Magnitudine Figurarum Curvilinearum, Latine scripti.

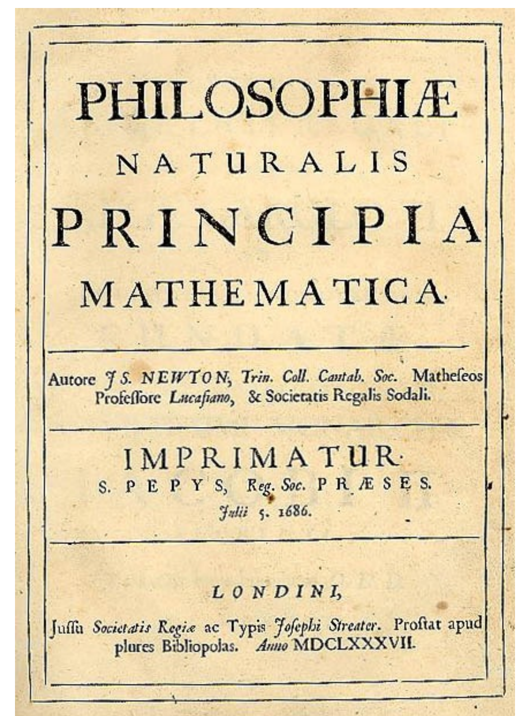
LONDINI:
MDCCVI.

But I have no idea what they are.

$F_{NET}=ma$







PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

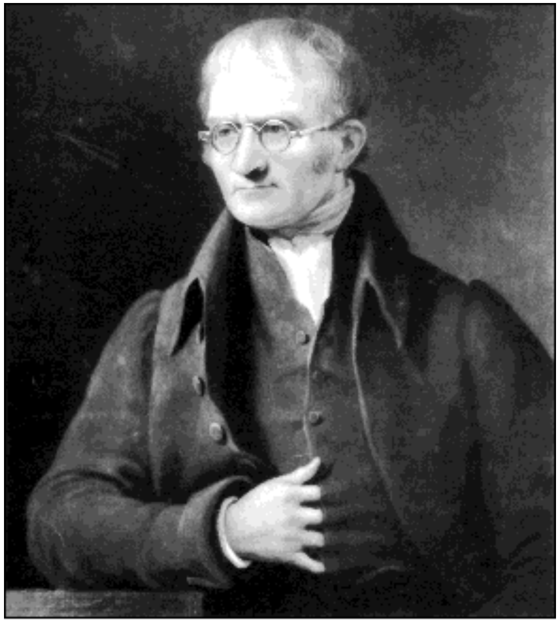
Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

Chemists Discover Evidence for Atoms

1802



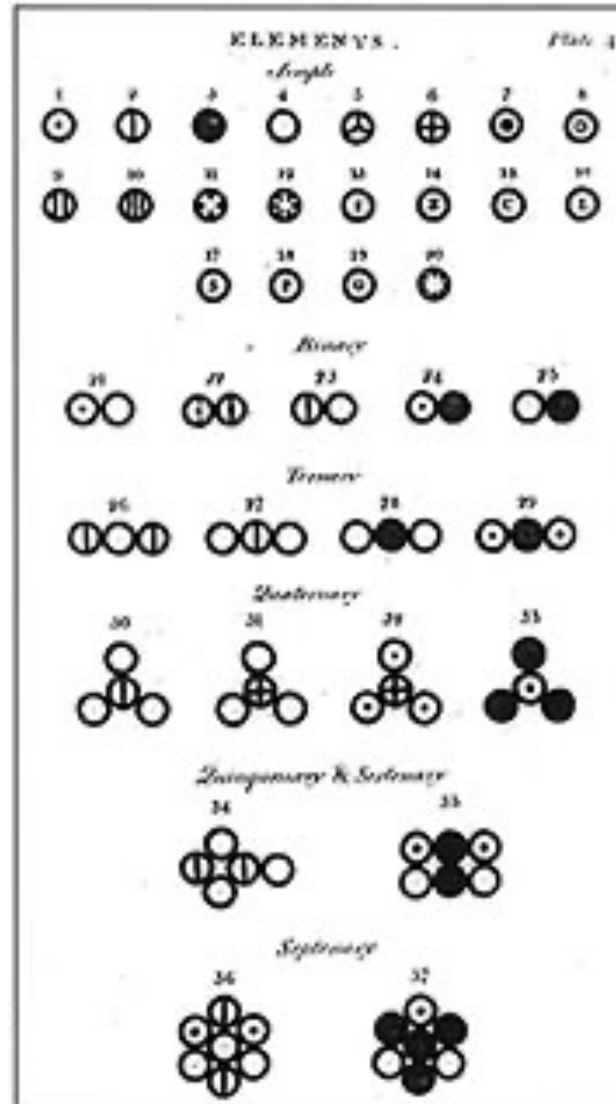
John Dalton

NO_2

N_2O

CH_4

C_2H_4



- Gay-Lussac's Law
- Boyle's Law
- Charles's Law
- Law of Multiple Proportions

World's First Particle Physicist

1827

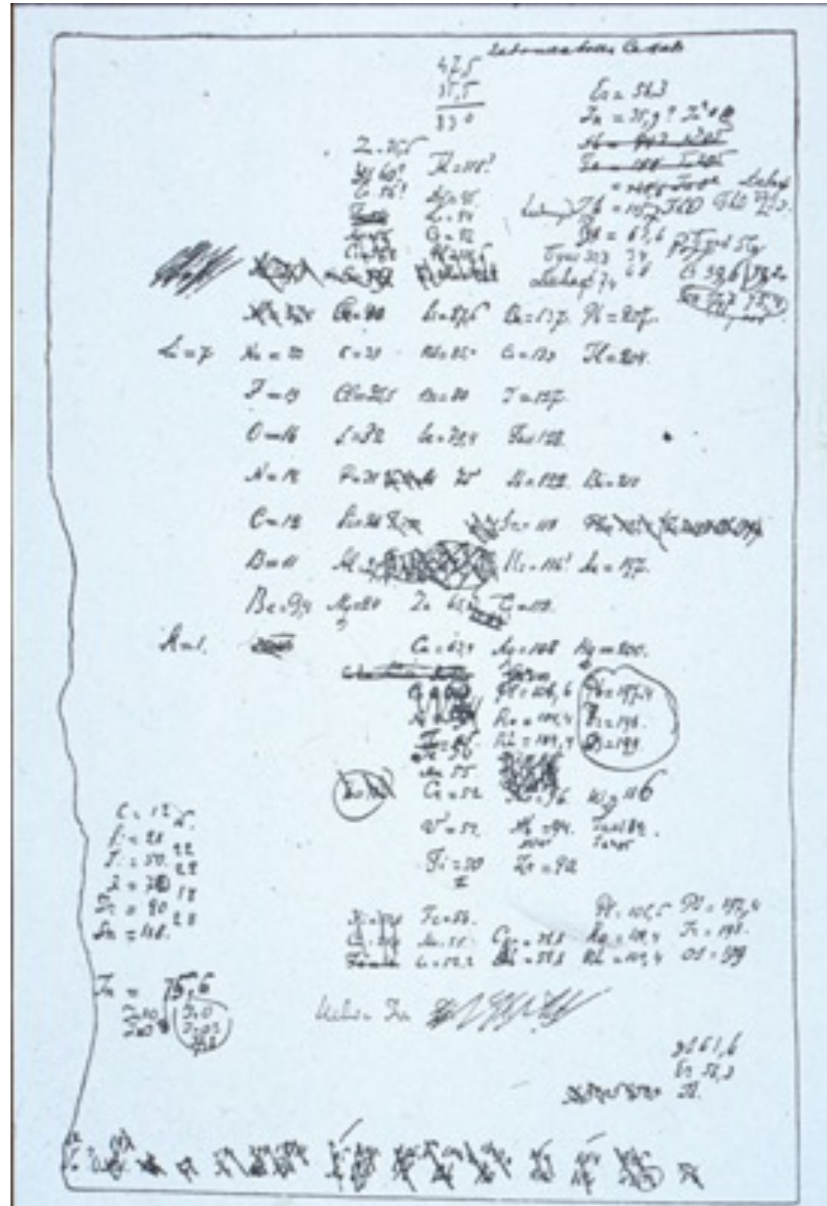
Robert Brown
-botanist (physicists experimentalist)
-discovered the "brownian" motion

Periodic Table

1869

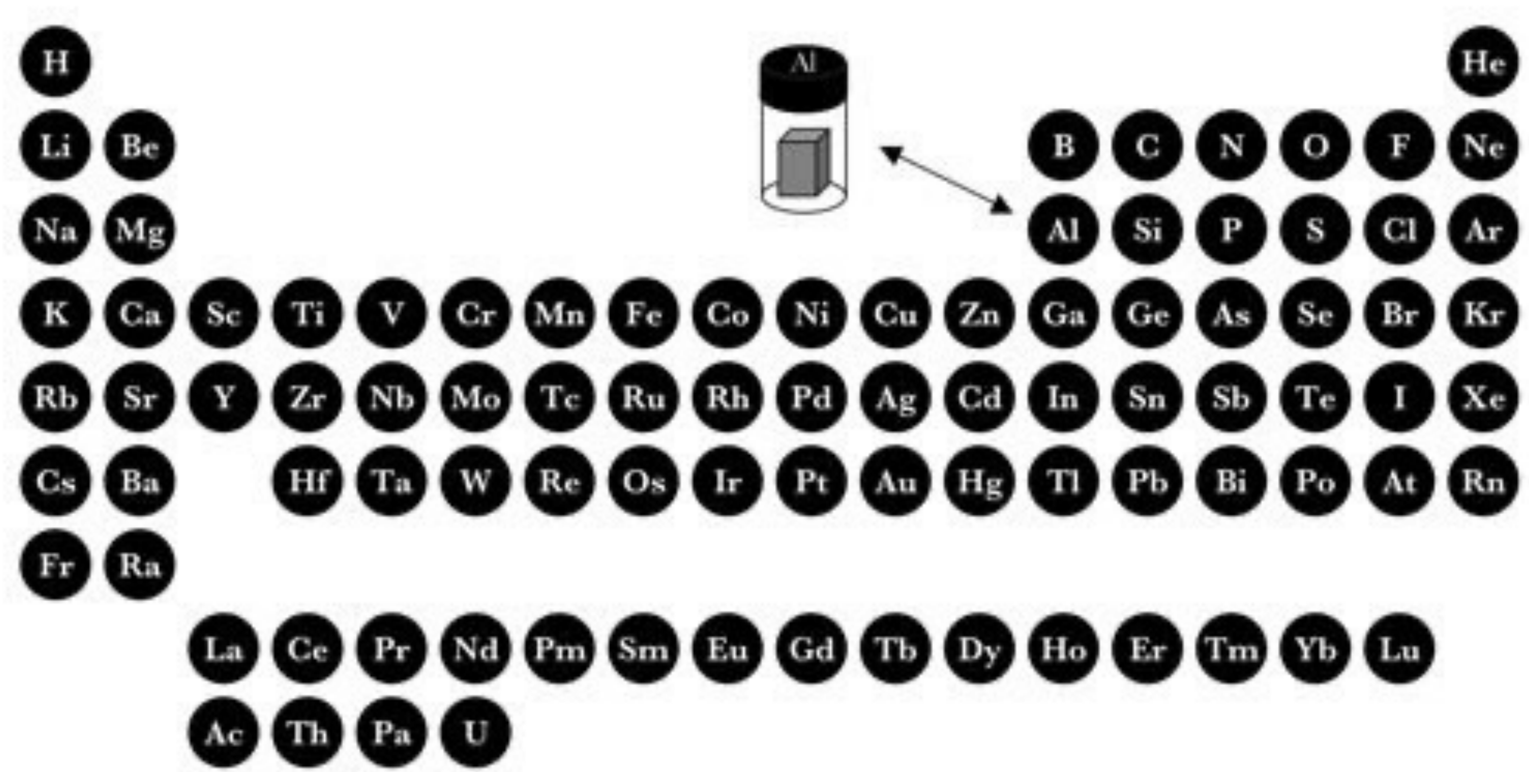
Mendeleev

-a classification scheme, … with holes



Fundamental Particle Physics

... by the end of 19th century, there were



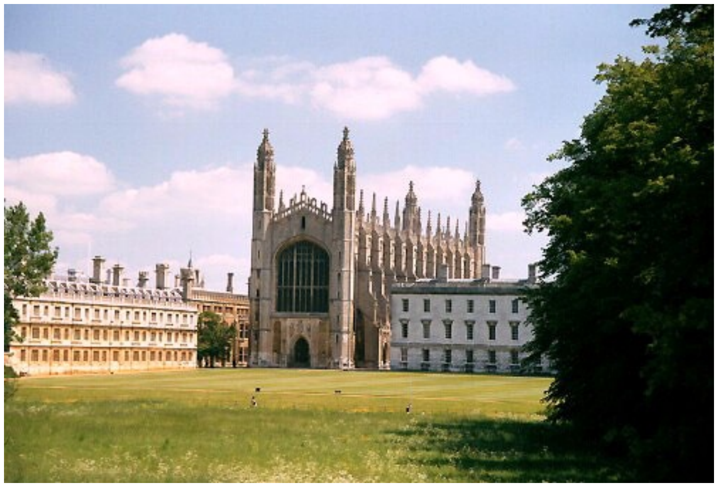
92 Atoms, U

The “Romantic” Period

~1897 – ~1932

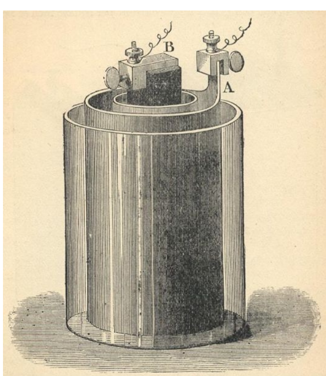
The Cavendish laboratory

World's premier physics laboratory late 19th century

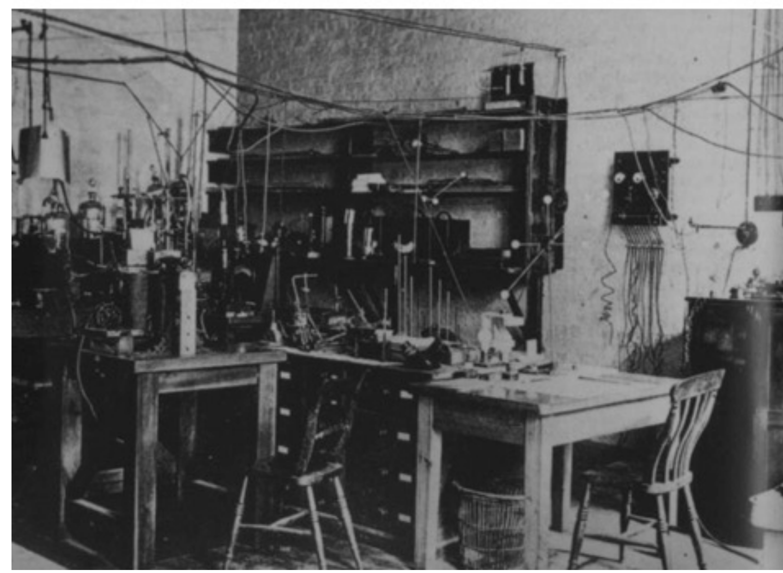


Cambridge University

The Cavendish Lab



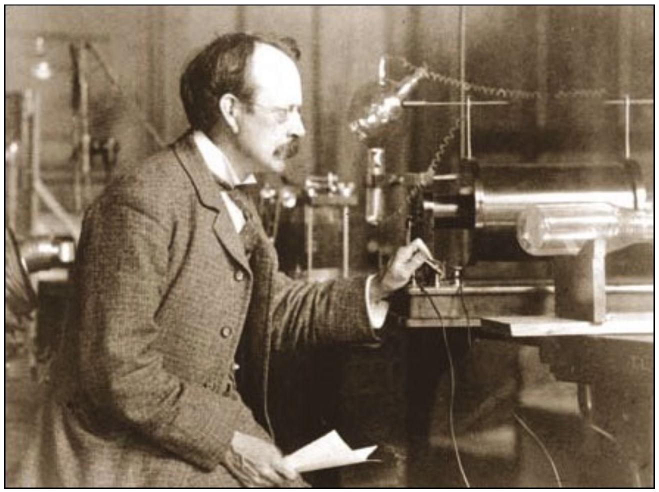
Bunsen Cell



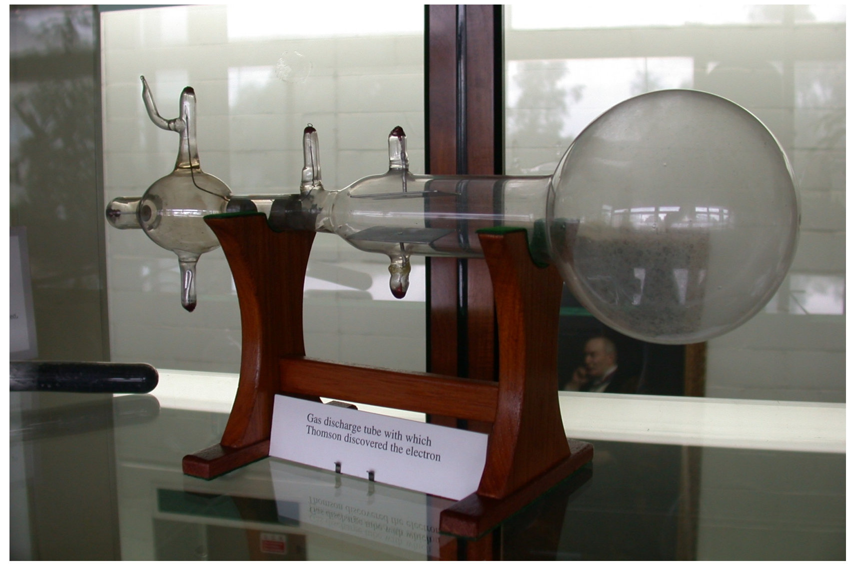
A Typical Lab

Discovery of the Electron

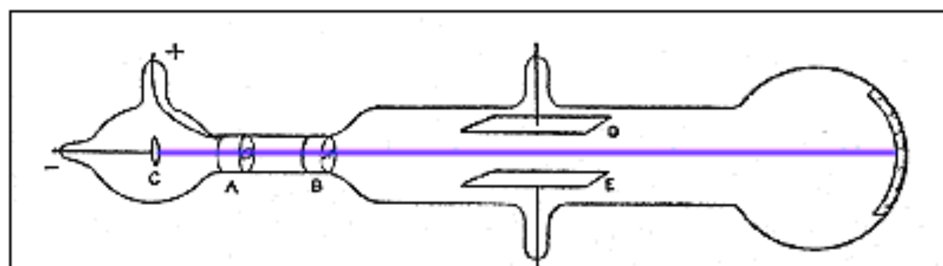
1899



J. J. Thomson



Thomson's CRT

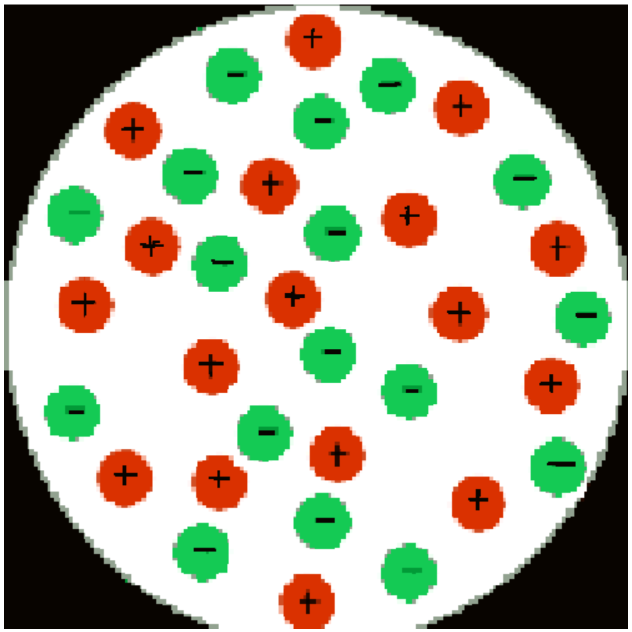


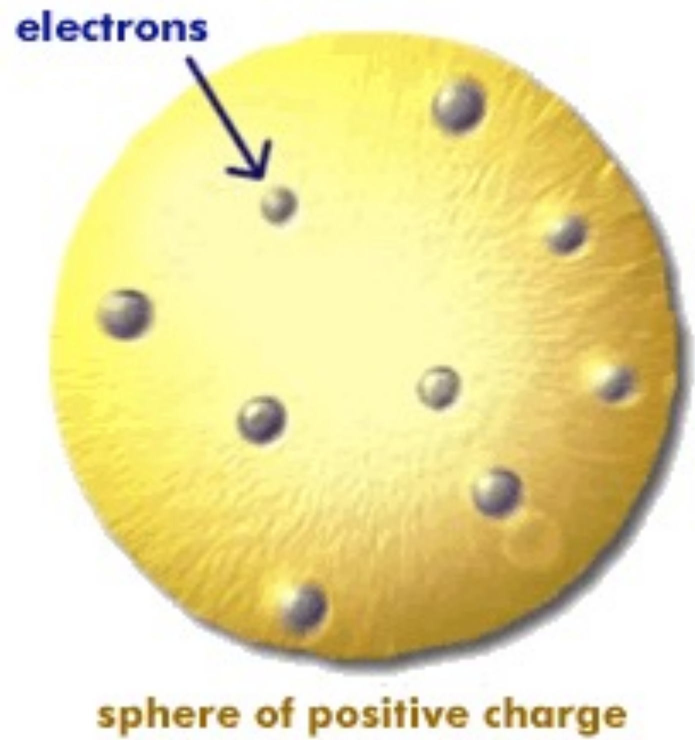
A new particle, "corpuscule"

electrically charged !

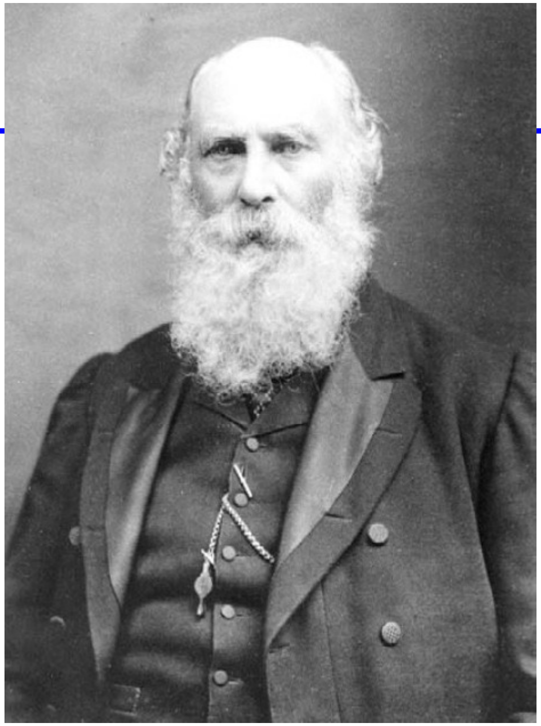
The "Plum Pudding" Model

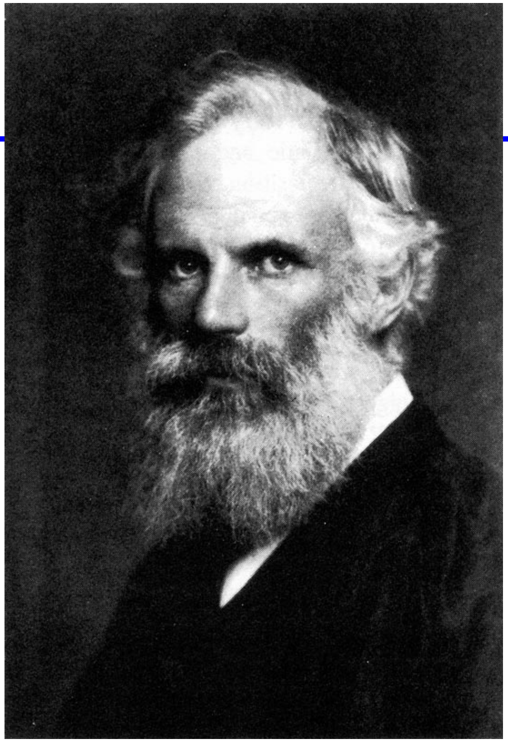
How to make a stable electrically neutral atom?





Negatively charge electrons distributed like raisins in a positively charged "pudding"





The term "electron" coined in 1891 by George Johnstone Stoney to denote the unit of charge found in experiments that passed electrical current through chemicals; Irish physicist George Francis Fitzgerald who suggested in 1897 that the term be applied to Thomson’s “corpuscles”.

The photoelectric effect

1887-Heinreich Hertz

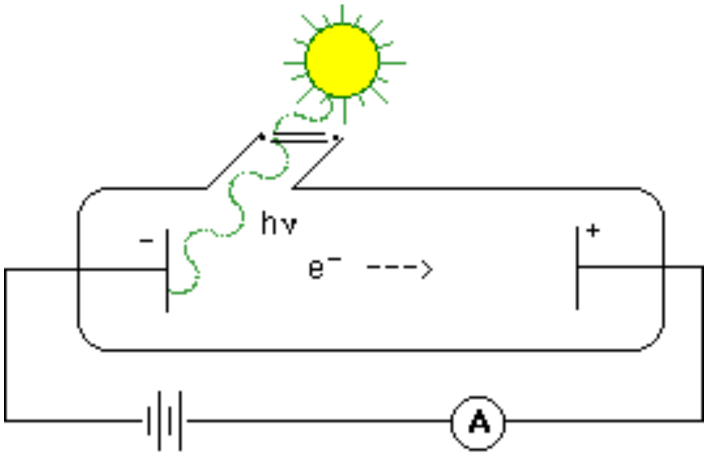
1895-Wilhelm Roentgen

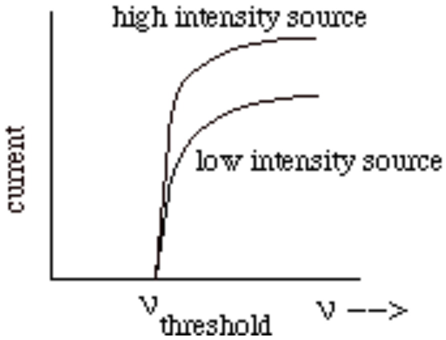
1899-J.J. Thompson

1901-Nikola Tesla

1902-Philipp von Lenard

1905-Albert Einstein





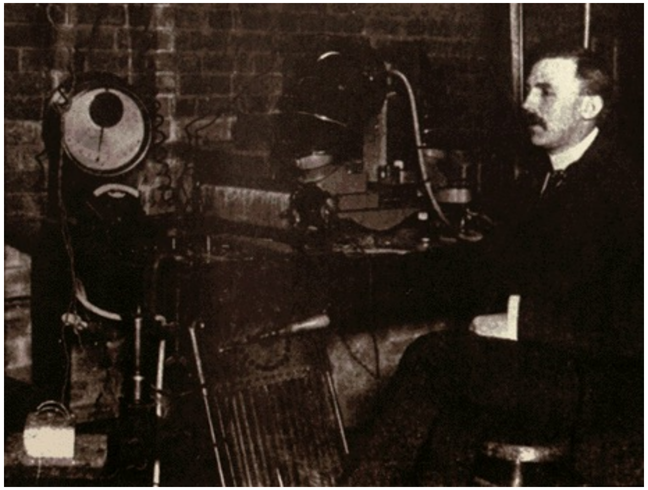
$$E = h\nu = W + \frac{1}{2}m_e v^2$$

Photons can knock electrons out of atoms

$\Rightarrow$ electrons are part of atoms

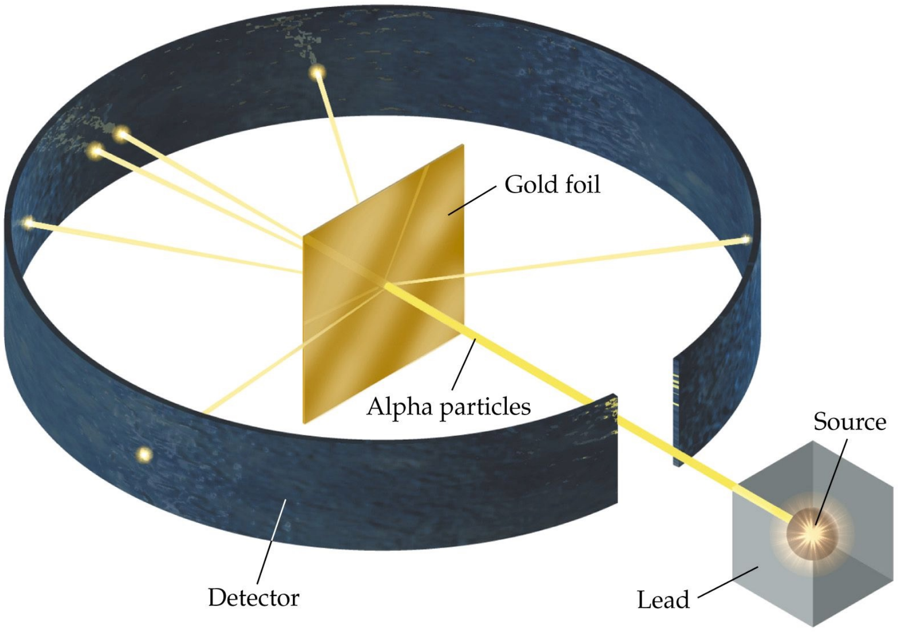
Lord Ernst Rutherford

1910 World's first high energy physicist



Ernest Rutherford

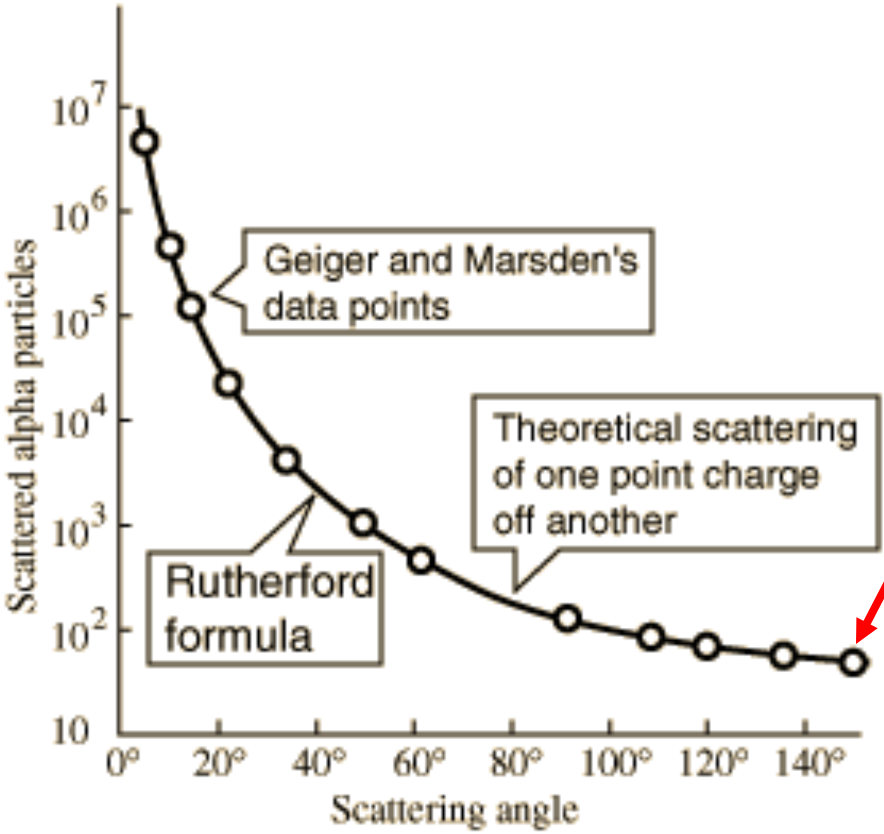
Use high energy (5 MeV) alpha particles from radium decay to study structure of the atom.



very light electrons should have no effect on the alpha's positive particle.

scattering of the alpha's will indicate structure of the "pudding"

Rutherford Scattering… surprise!



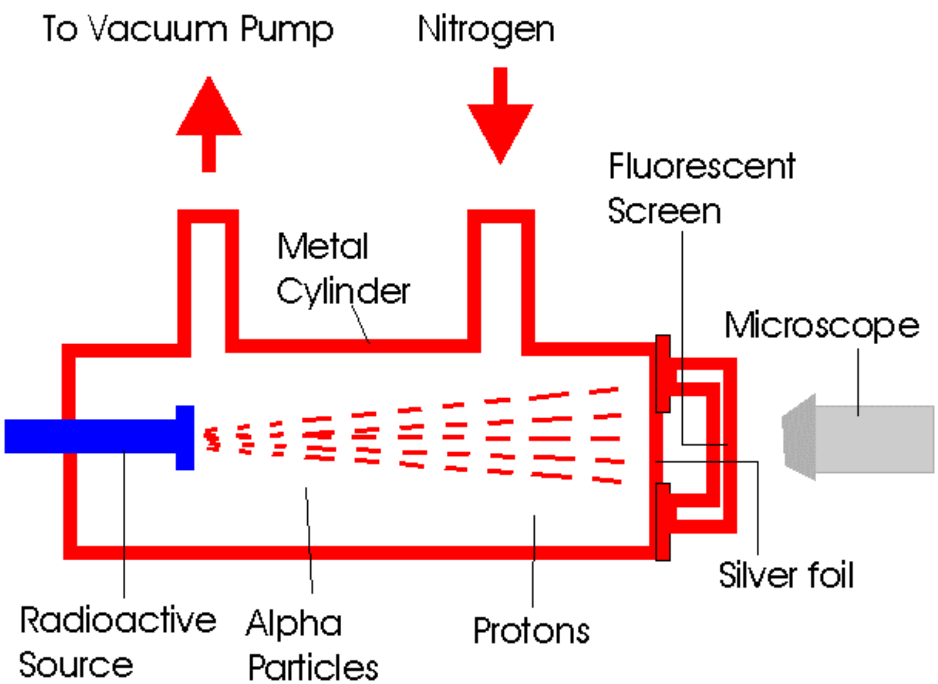
some of the alpha's scattered at large angles

Data is described by **assuming** that alpha particle is scattered of a massive positive point charge.

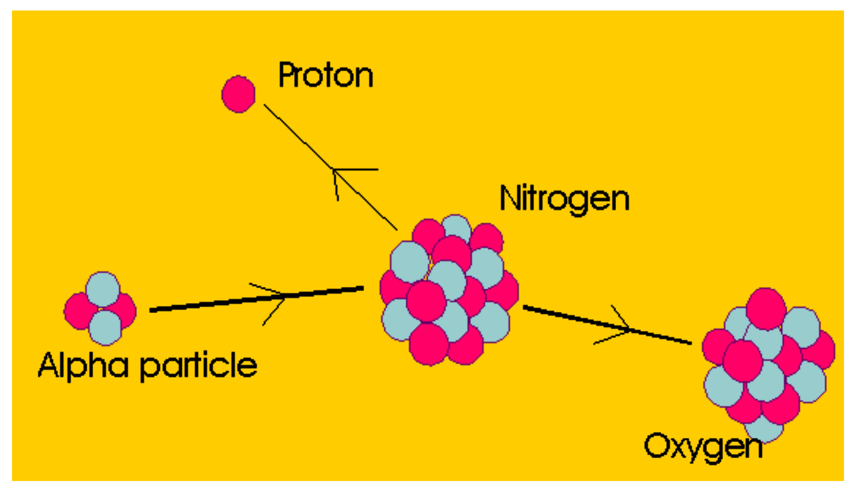
$$\frac{d\sigma}{d\cos\theta} = \frac{\pi Z^2 z^2 \alpha^2 \hbar^2 c^2}{2E_k^2} \frac{1}{(1-\cos\theta)^2}$$

Discovery of proton

~1911, Lord Rutherford also discovers the nucleus of hydrogen (the proton, p+, "first" in Greek) by bombarding alpha particles (^4_2He) with Nitrogen gas



$$^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}p$$

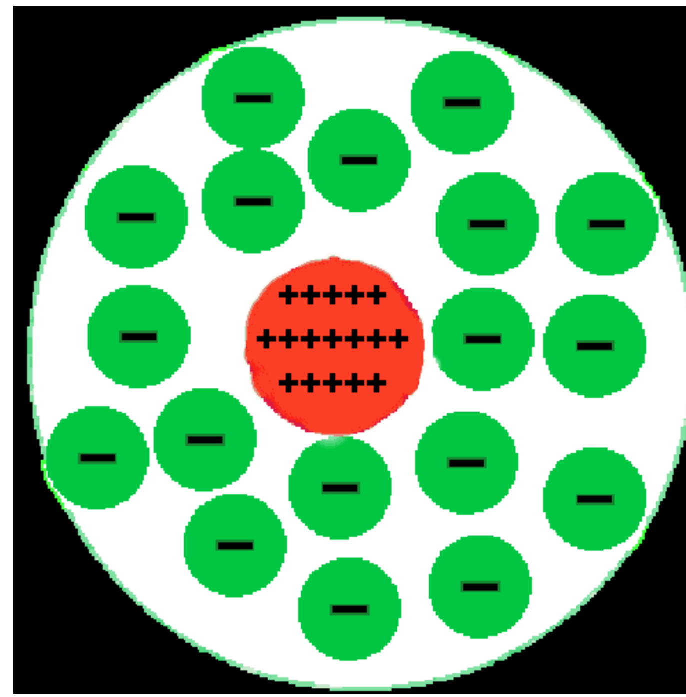


More questions than answers …

-Scientists were puzzled by the missing mass as protons' mass did not add up to atom's;

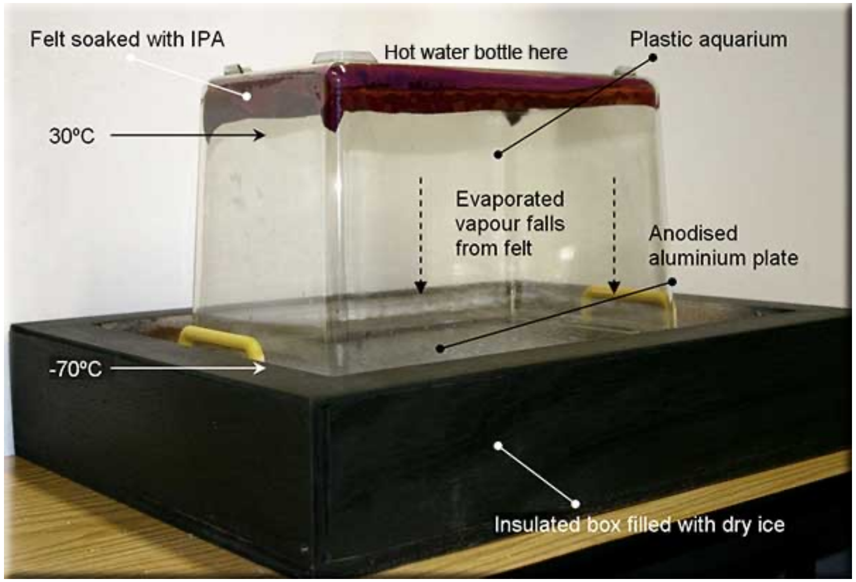
-Rutherford predicts theoretically the presence of a neutral particle;

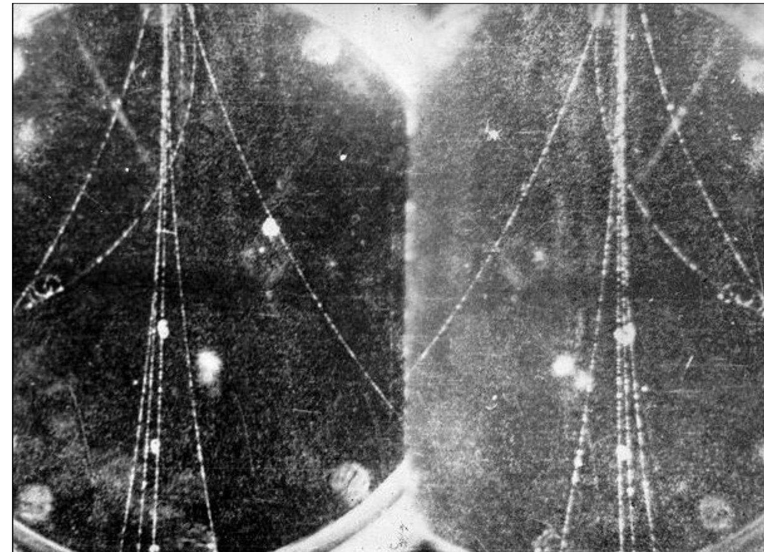
-Bothe-Becker, Joliot-Curie discovered highly penetrating rays (even thru lead) from Be radiation;



Rutherford's model

Wilson's Cloud Chamber

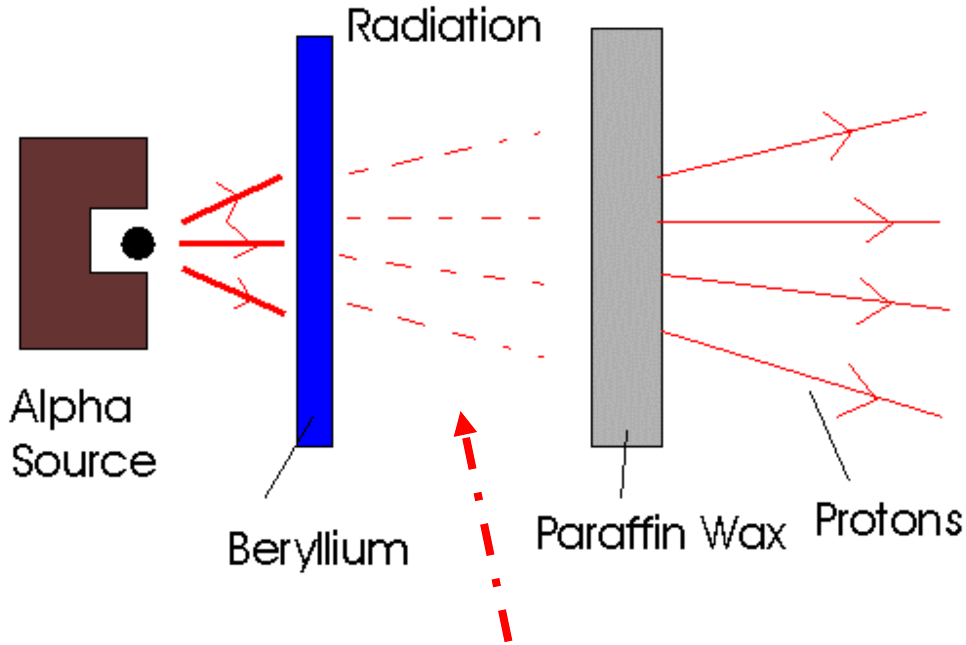




When a charged particle passes through a supersaturated gas, a series of droplets marking the path of the particle condenses out of the vapor, as the particle ionizes atoms along the track. These tracks are momentarily visible, marking the path of the particle through the detector, taking photographs of any visible tracks.

Discovery of the neutron

James Chadwick



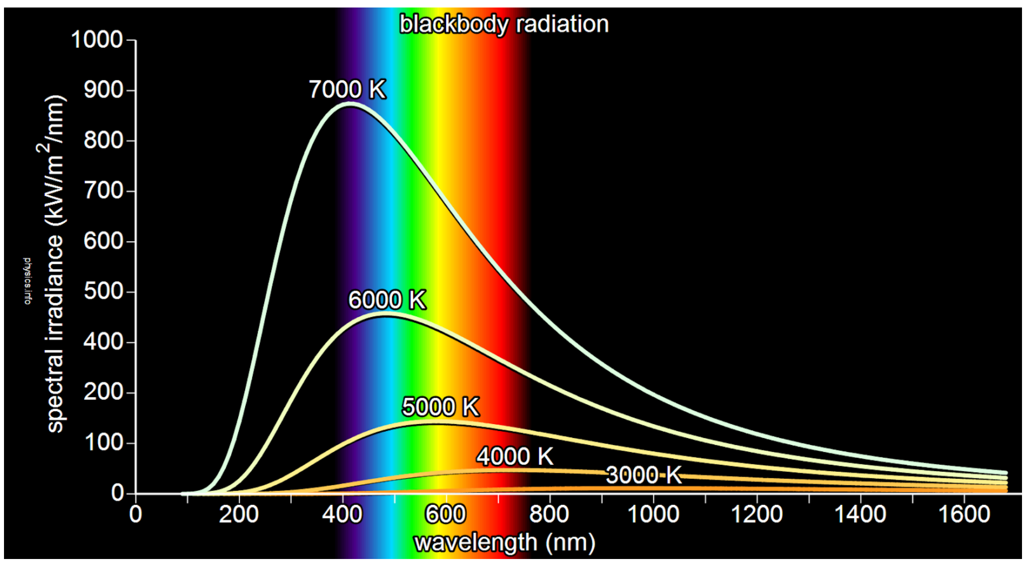
Radiation of beryllium, immune to E and B fields (beam of neutrons)

$$^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + ^{1}_{0}n$$

The basis for the word neutron is both "neutral" and the suffix "-on," which comes from the Greek word “ión” meaning "to go." The word ion first appeared in English in 1834, and neutron appeared in 1921.

Stefan-Boltzmann, Wien and Max Planck

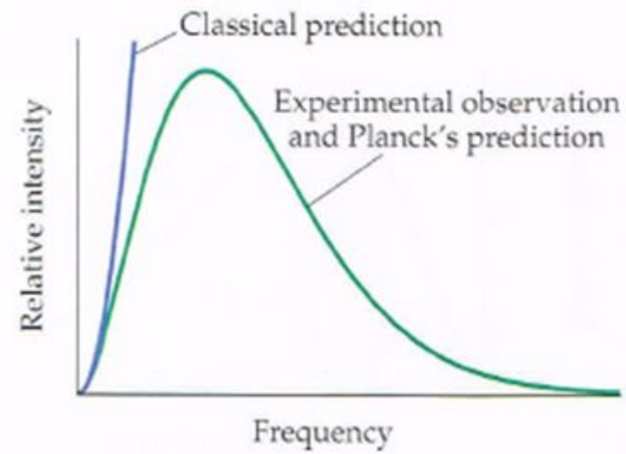
- black body radiation-relation between an object's temperature and wavelength of radiation it emits



~1900s

Planck's Quantum Hypothesis

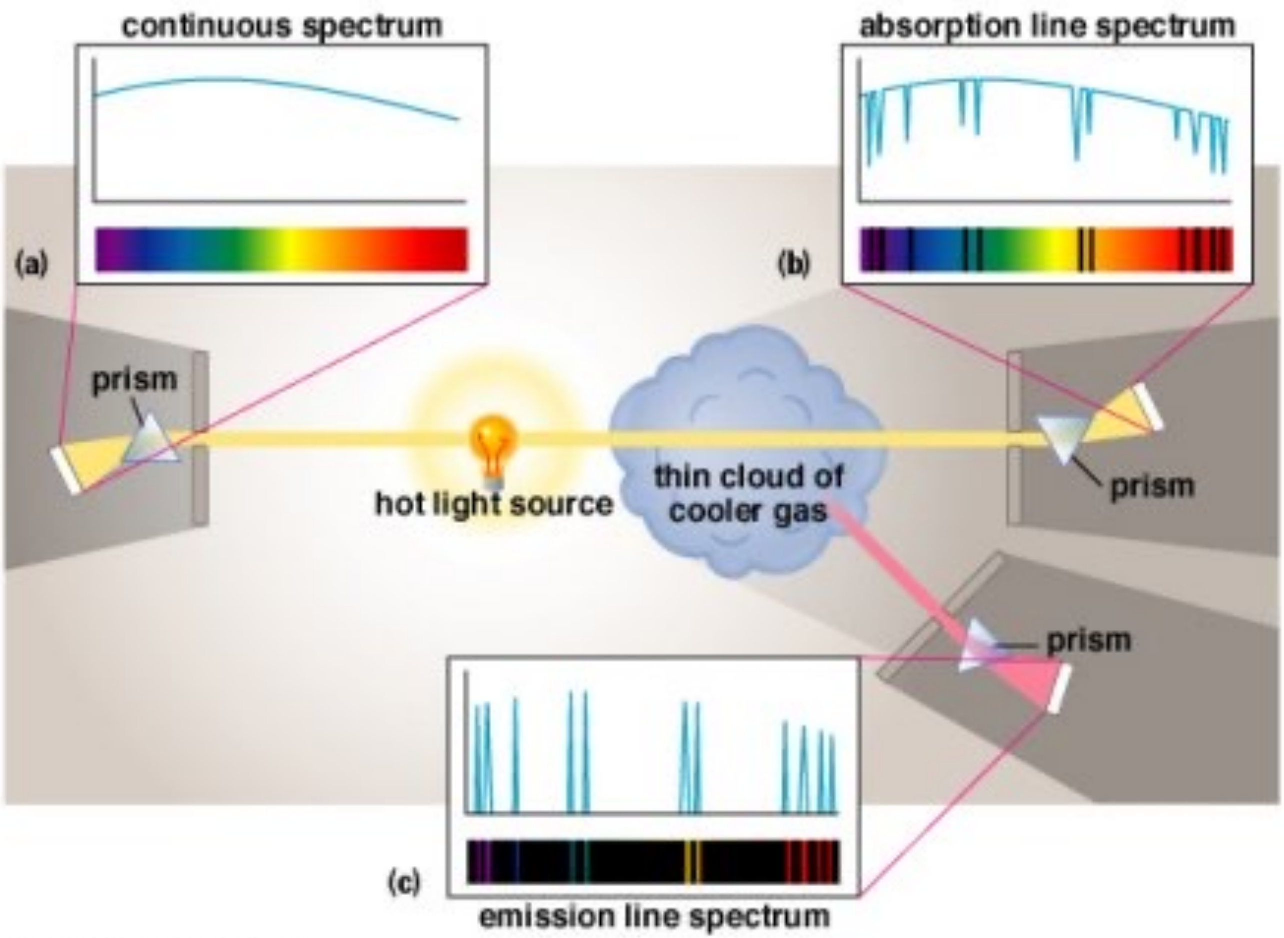
- Attempts to explain blackbody radiation using classical physics failed miserably
  - At low temps. Prediction & exp match well
  - At high temps. Classical prediction explodes to infinity
  - Very different from experimental result
  - Referred to as the Ultraviolet Catastrophe



▲ **FIGURE 30–3 The ultraviolet catastrophe**

Classical physics predicts a blackbody radiation curve that rises without limit as the frequency increases. This outcome is referred to as the ultraviolet catastrophe. By assuming energy quantization, Planck was able to derive a curve in agreement with experimental results.

Continuous, absorption and emission spectra (Fraunhofer, Kirchhoff …) - spectroscopy.



Matter waves

In 1924, de Broglie suggested that the matter particles will have associated waves known as de Broglie waves or matter waves

de Broglie Wavelength

$$\lambda = \frac{h}{p} \ (or) \ p = \frac{h}{\lambda}$$

de Broglie Wavelength in terms of KE

Consider a particle of mass *m* moving with a velocity *v*

Kinetic Energy of the particle

$$E = \frac{1}{2}mv^2 = \frac{1}{2m}m^2v^2 = \frac{p^2}{2m}$$

$$E = \frac{p^2}{2m} \Rightarrow p^2 = 2mE \Rightarrow p = \sqrt{2mE}$$

Louis de Broglie

de Broglie wavelength

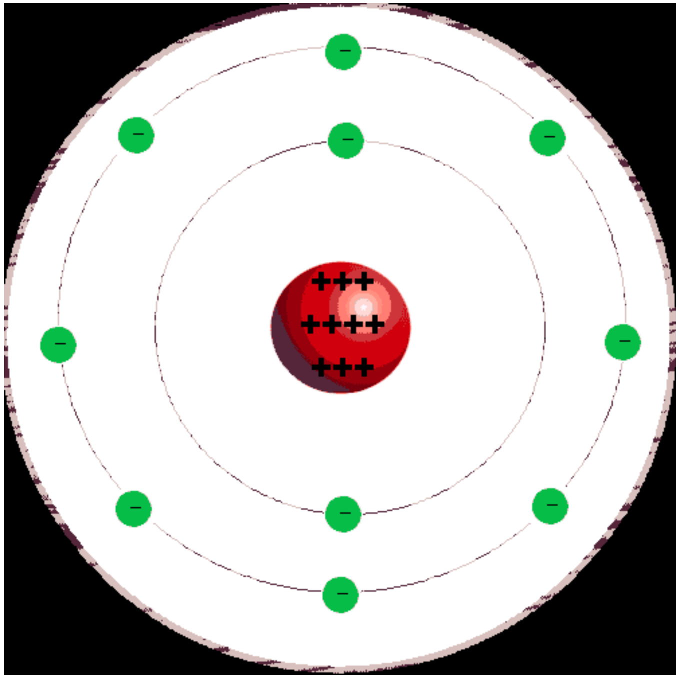
$$\lambda = \frac{h}{p}$$

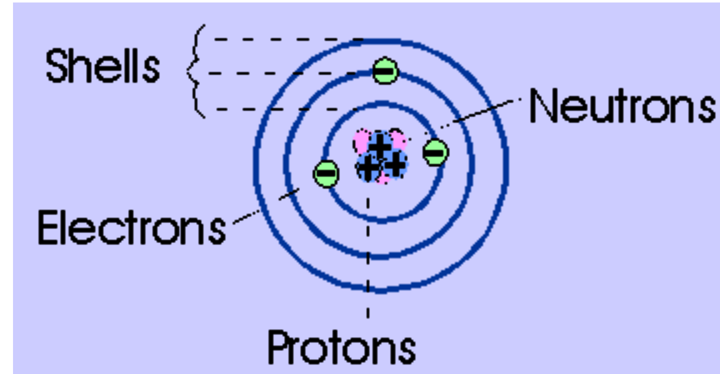
de Broglie wavelength in terms of KE

$$\lambda = \frac{h}{\sqrt{2mE}}$$

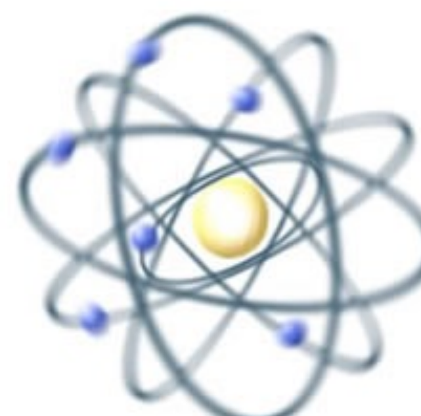
Education for an inspired life. Joshi Physics Classes

Bohr's model of atom ~1913





Nearly all of the mass of the atom is concentrated in a very small positively charged nucleus.

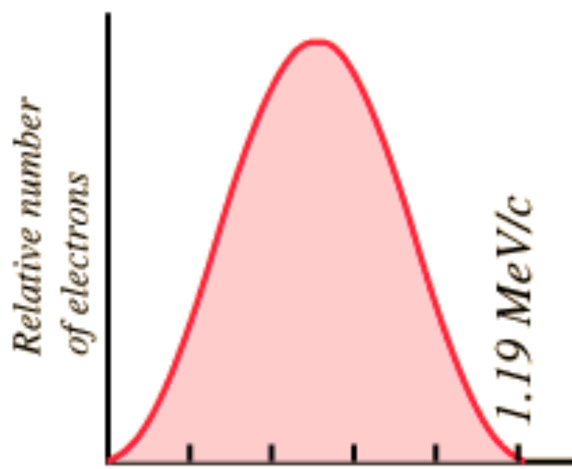


How small is the nucleus?
What holds it together?

The Neutrino

A free neutron decays to a proton and electron in about 15 minutes. From conservation of momentum and conservation of energy…

- not a 2-body decay
- must be a third unseen particle



$$n \rightarrow p + e^{-} + \bar{\nu}$$

“ghost-like” particle

Predicted theoretically in 1930 by Wolfgang Pauli.

Discovered in 1956 by Cowan and Reines.

Fundamental Particles by …

1932

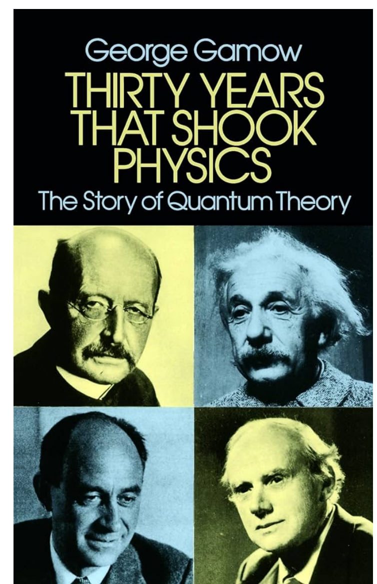
neutrino ν

electron e^-

photon γ

proton p

neutron n



Heisenberg Uncertainty Principle

precision of measurement

momentum transferred

$$\Delta x \approx \frac{\hbar}{\Delta p}$$

where $\hbar \approx 6.32 \times 10^{-32}$ Js

Why we need large, expensive high energy accelerators?

If you want to probe something at small distances, you have to kick it hard!

Heisenberg Uncertainty Principle

$$\Delta E \Delta t \geq \frac{h}{2\pi}$$

The more accurately we know the energy, less accurately we know how long it possess that energy.

The energy can be known with perfection, $\Delta E=0$, only if measurement is made over a long period of time $\Delta t=\infty$

The "Modern" Period

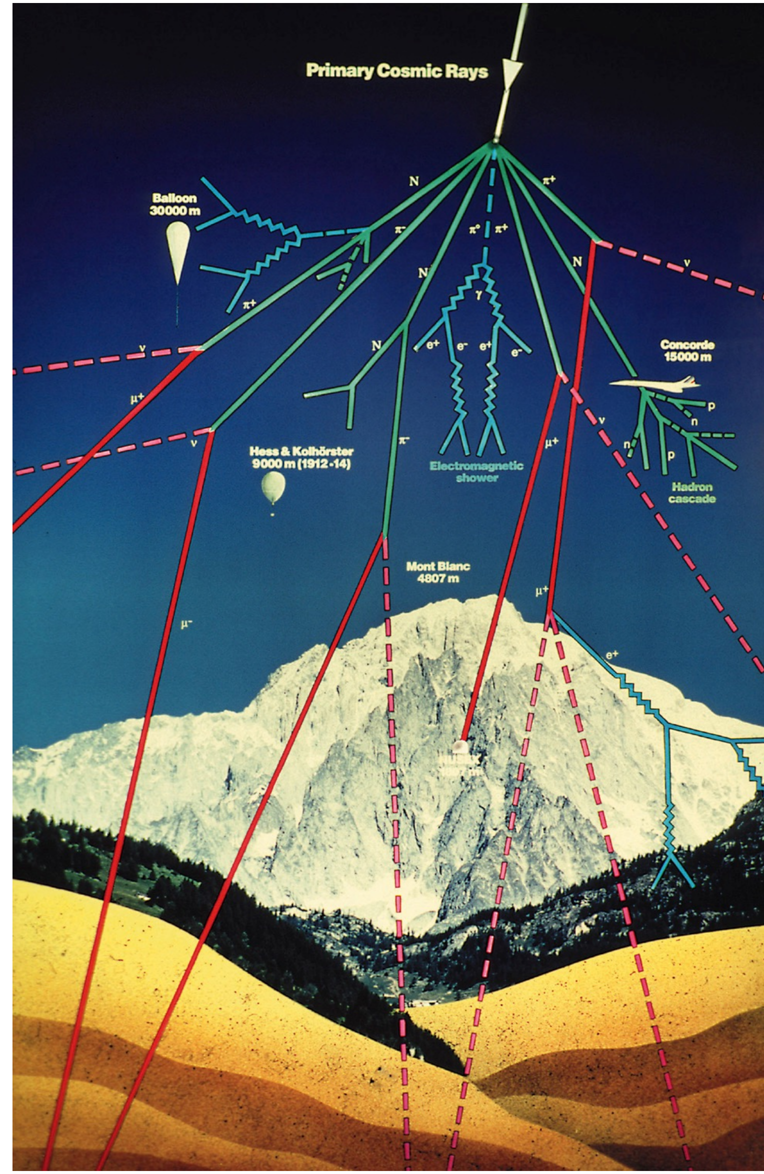
1932 – 1974

Cosmic Rays-the cosmic accelerator

-Becquerel: ionization of air caused by radioactive elements underground;

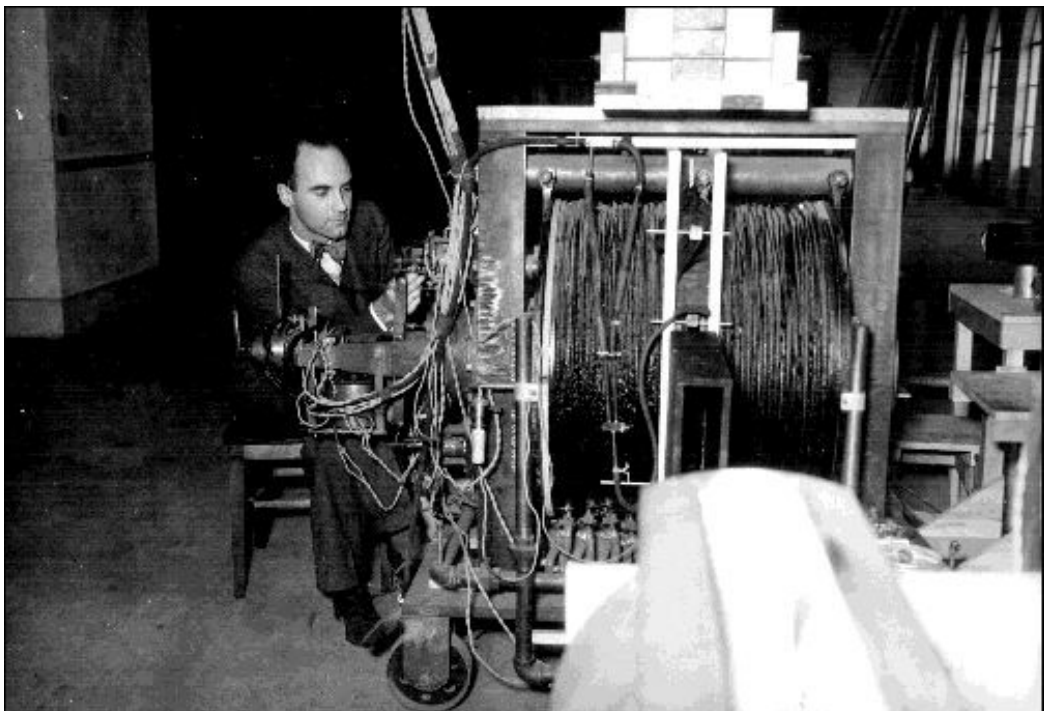
-Victor Hess measures air ionization level in a balloon: “radiation of high energy enters from above”.

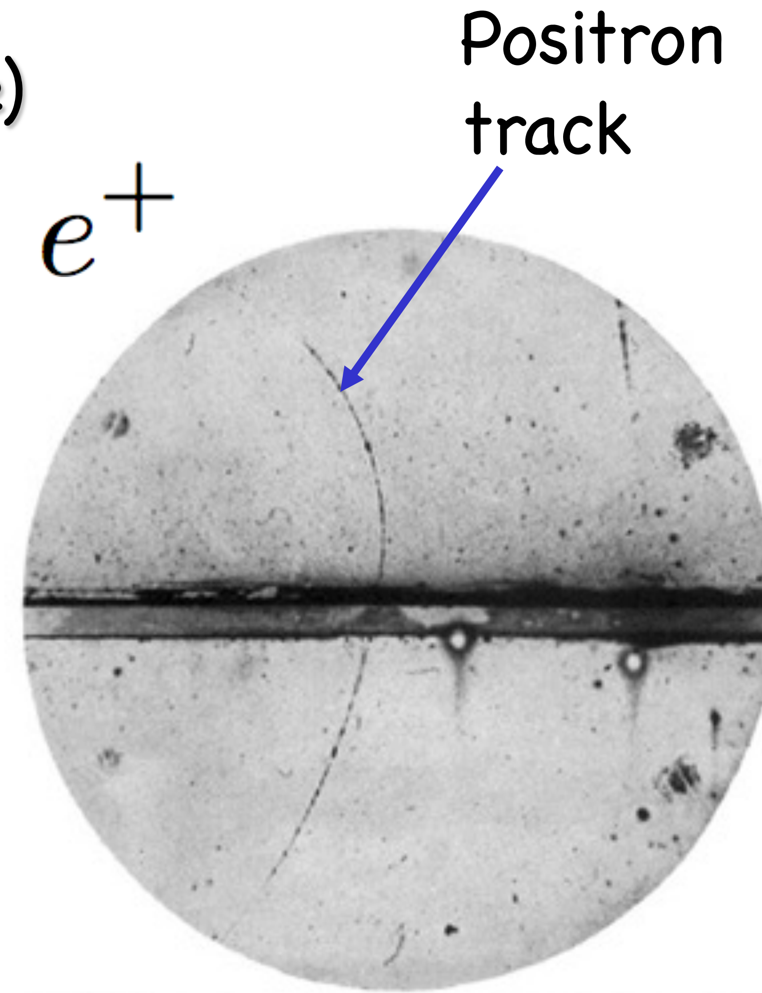
-much higher energies than available in the lab: higher energies could produce more massive particles.



Antimatter

1932-Carl D. Anderson discovers the anti-electron, the **positrons**
(same mass, but positive charge)





Discovery of the Muon

1937-also Anderson discovered a heavy electron (105.7 MeV/c^2) - the **muon**

μ

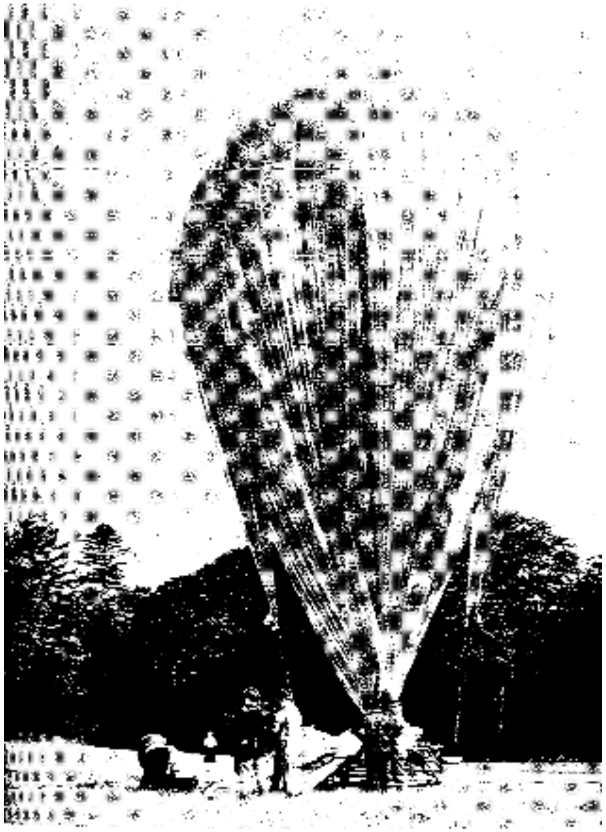
Same charge just like the electron, but about 200 times more massive.

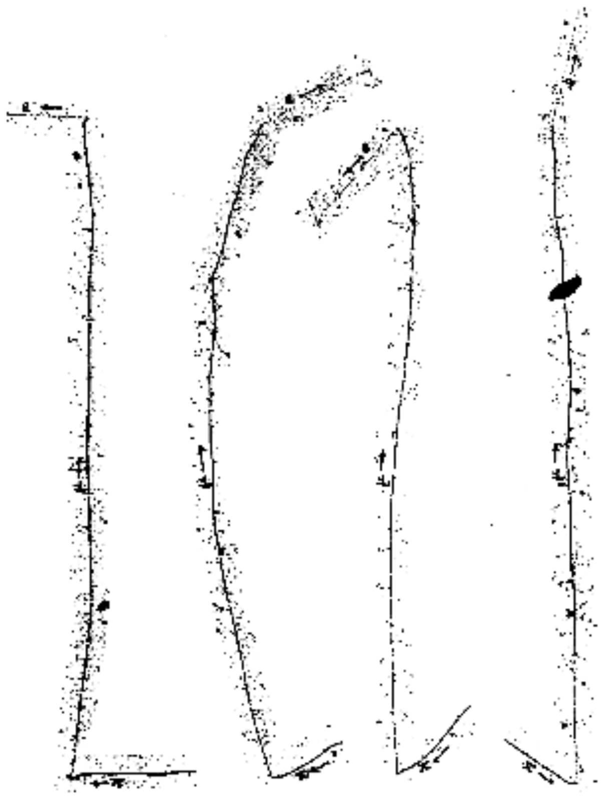
Isaac Rabi

Particles Discoveries

1935, pions were theoretically predicted by Hideki Yukawa

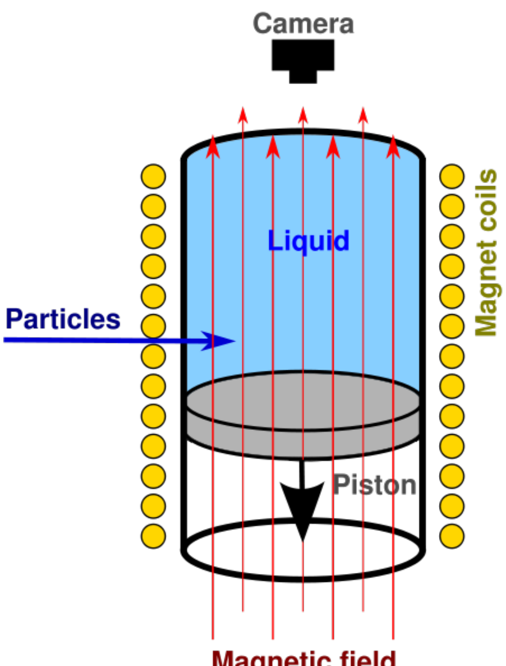
1947: **pions** were discovered using photographic emulsions at high altitudes





1952-The Bubble chamber

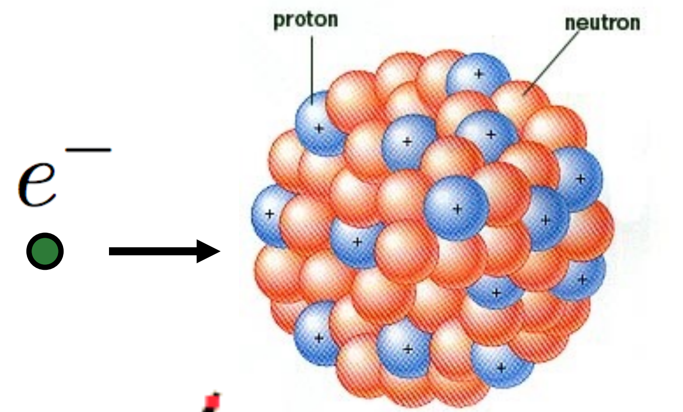
Donald Glaser

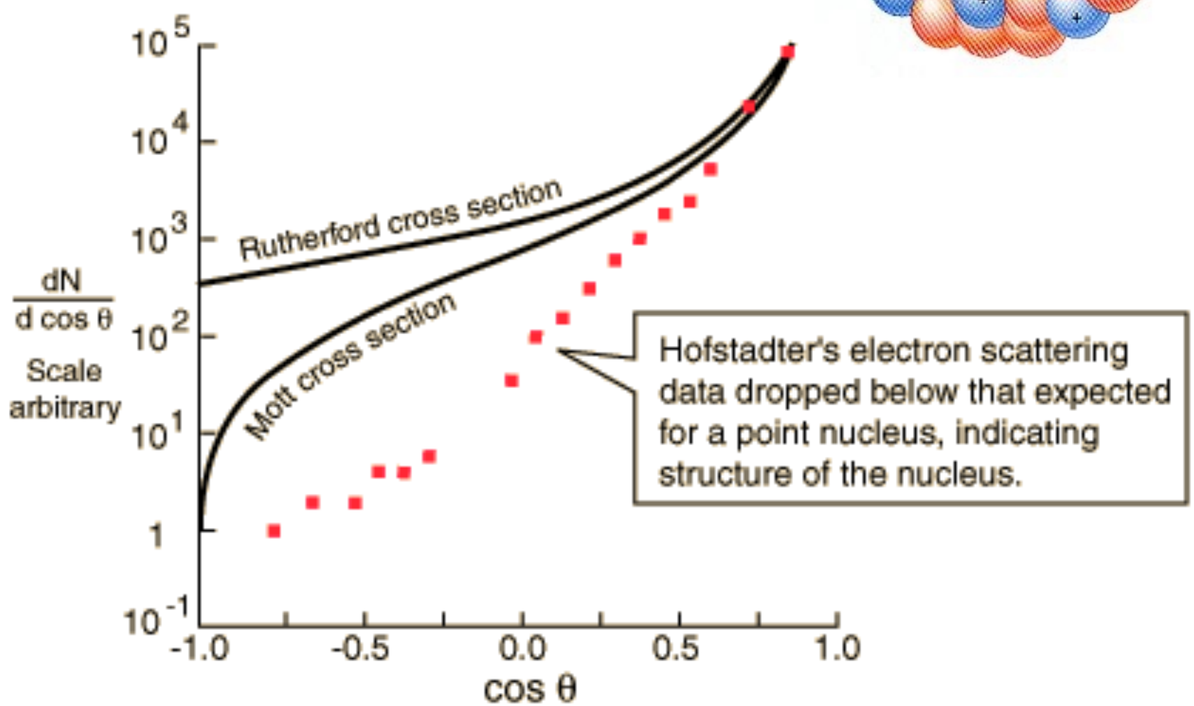


The bubble chamber is made by filling a large cylinder with liquid hydrogen heated to just below its boiling point. As particles enter the chamber, a piston suddenly decreases its pressure, and the liquid enters into a superheated phase. Charged particles create an ionization track, around which the liquid vaporizes, forming microscopic bubbles. Bubble density around a track is proportional to a particle's energy loss.
Bubbles grow in size as the chamber expands, until they are large enough to be seen or photographed. Several cameras are mounted around it, allowing a three-dimensional image of an event to be captured. Bubble chambers with resolutions down to a few μm have been operated.
The whole chamber is subject to a constant magnetic field, which causes charged particles to travel in helical paths whose radius is determined by their charge-to-mass ratios..

Structure of the Nucleus

1953 –Hofstadter scattered 125 MeV(10^6eV) electrons off of nuclei.

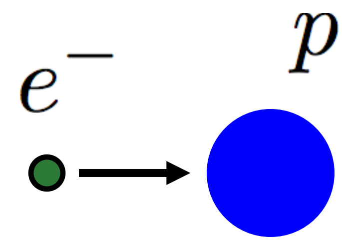


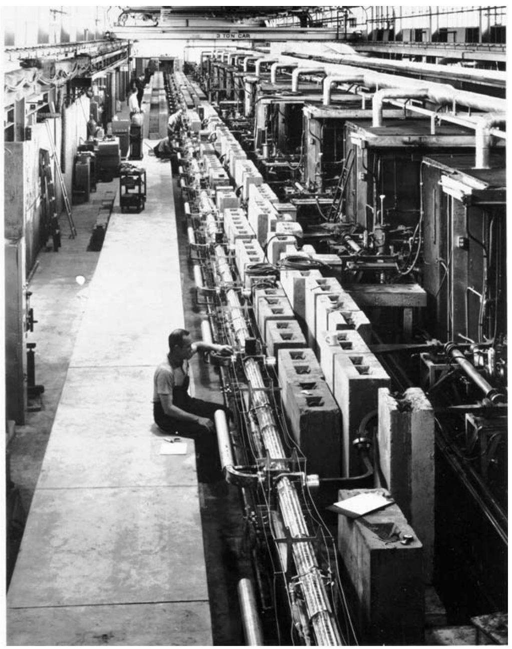


nuclear size: ~10^{-13} cm

Structure of the Proton

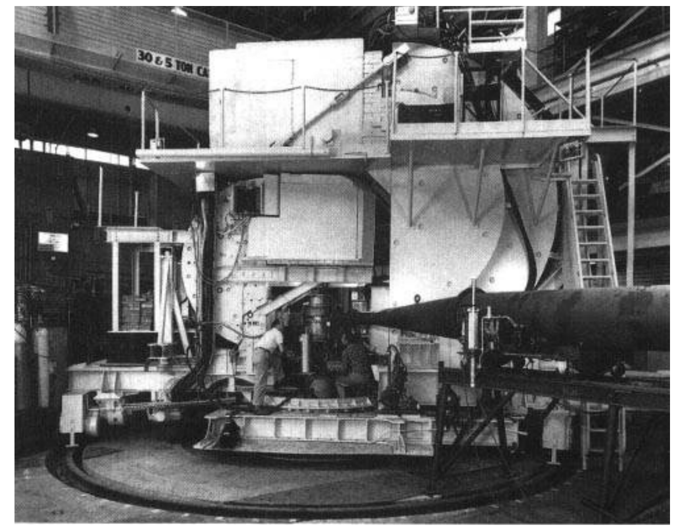
1956–Hofstadter scattered 550Mev electrons off of a proton.





$$W = qV = \frac{mv^2}{2} = KE$$

$$v = \sqrt{\frac{2qV}{m}}$$



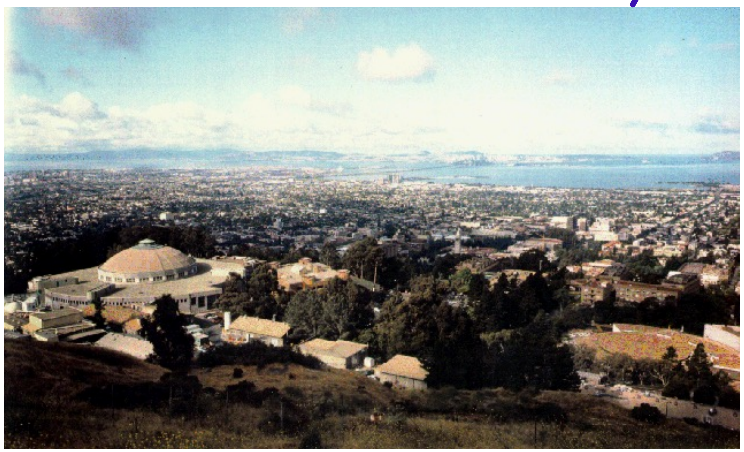
Spectrometer

Electron Linear Acc at Stanford University (SLAC)

The proton has a size, it is not a point-like object.

The Bevatron (1954-1993)

6 GeV proton synchrotron
in the hills of Berkeley



$$F_{mag} = F_{centripetal}$$

$$qvB = \frac{mv^2}{r}$$

$$r = \frac{mv}{qB}$$

Designed to discover
the anti-proton

More particles – Particle Data Group

https://pdg.lbl.gov/index.html

Δ (Delta) particle,

Σ (Sigma) particle,

Kaon - Caltech,

Antiproton - Berkeley, Segre&Chamberlain

η (Eta) particle,

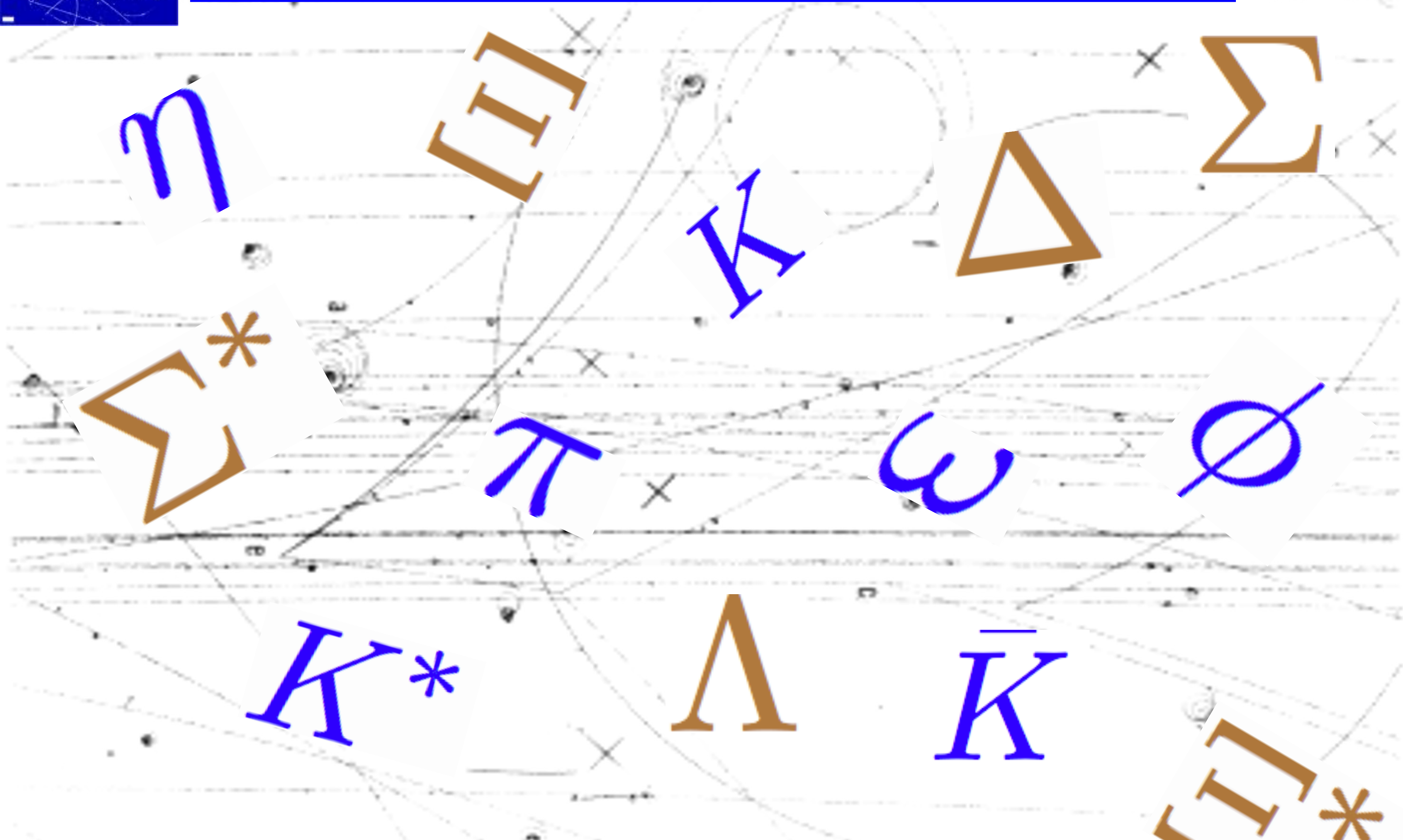
Ξ (Xi) particle - Brookhaven

Λ (Lambda) particle,

Tau particle - SLAC/LBL (Stanford and Berkeley)

…

The Particle Zoo (1955-1965)



What does it all mean?

A classifications is needed

NAMES, CONSERVATION LAWS, RULES

Classical: energy, mass, linear momentum, angular momentum

Q-electric charge (…,-1,0,+1,…)

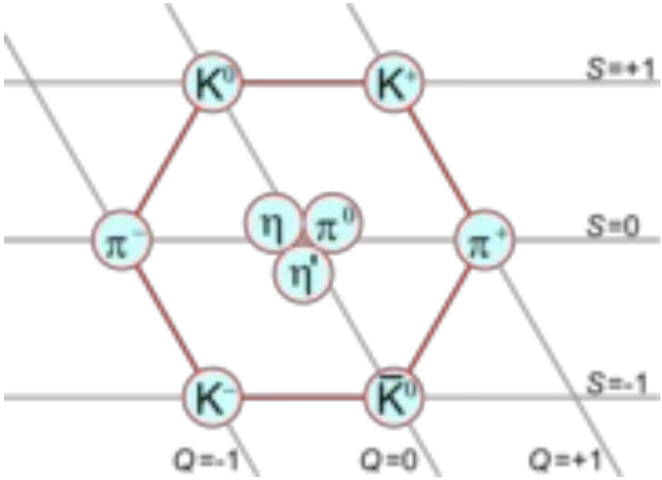
S-strange number (…,-2,-1,0,+1,+2,…)

B-Baryon number (-1, 0, +1)

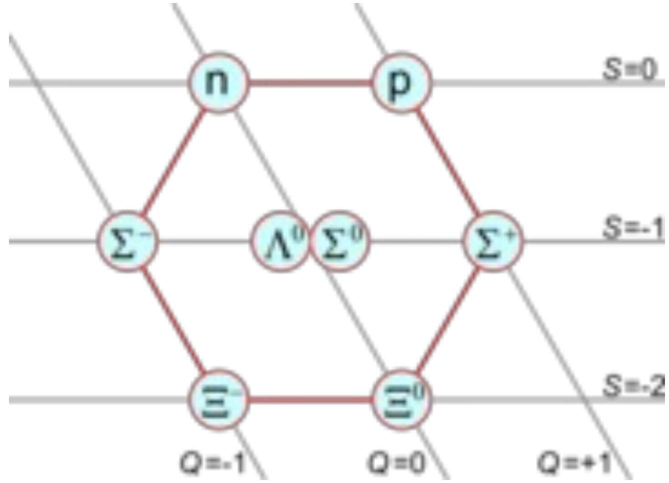
L-lepton number (-1, 0, +1)

Mesons (2 quarks), Baryons (3 quarks), Leptons, Bosons, …

Classification … Again



meson octet

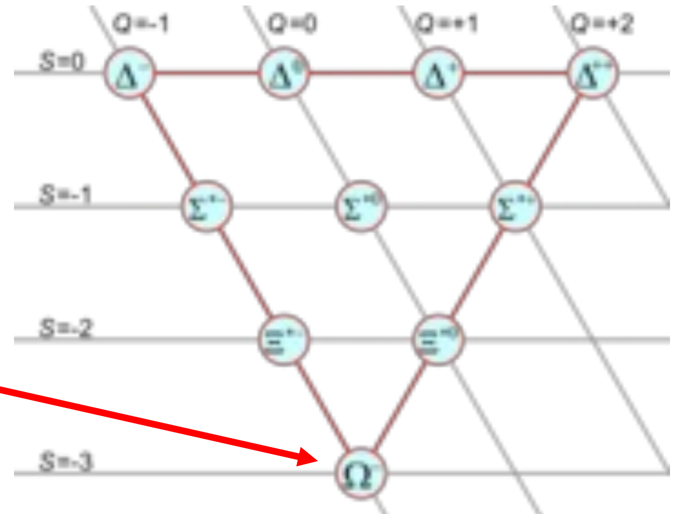


baryon octet

prediction:

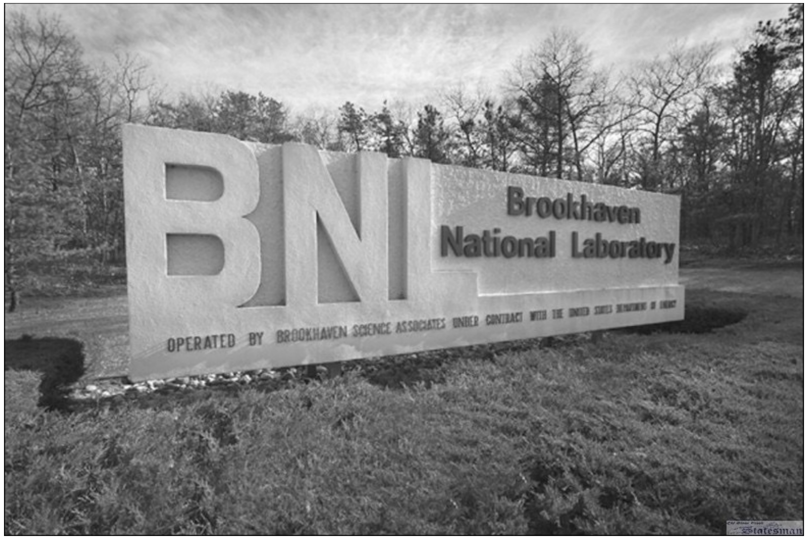
Ω^{-}

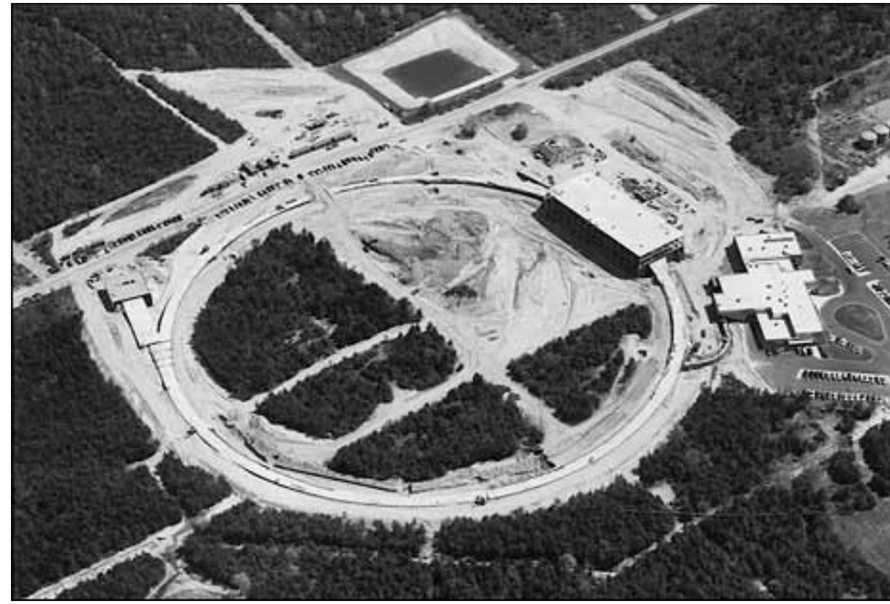
bound state of
3 strange quarks



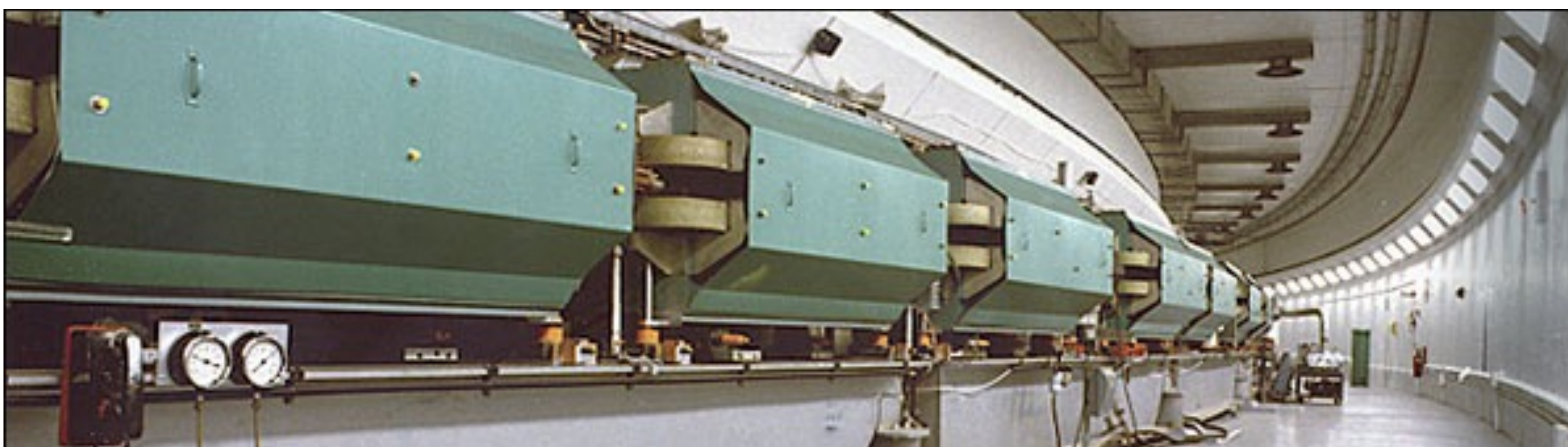
baryon decapet

Brookhaven National Lab (BNL), 1947





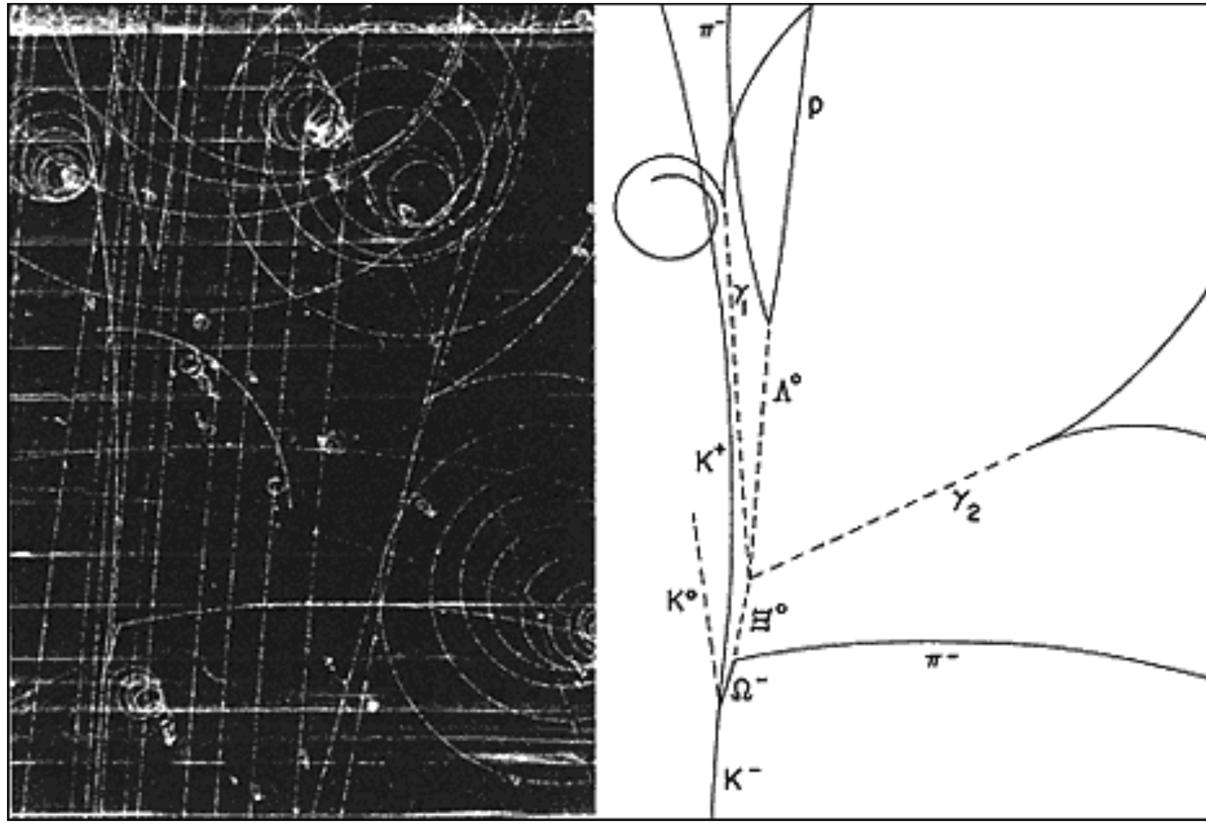
33 GeV proton synchrotron

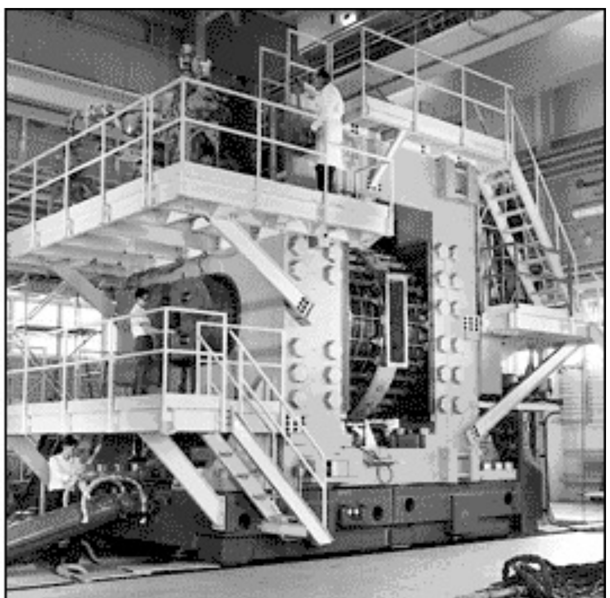


Discovery of the Omega Minus

1964

Nick Samios





80-inch bubble chamber

Who with who collision?

Stanford Linear Accelerator Center (SLAC) , 1962

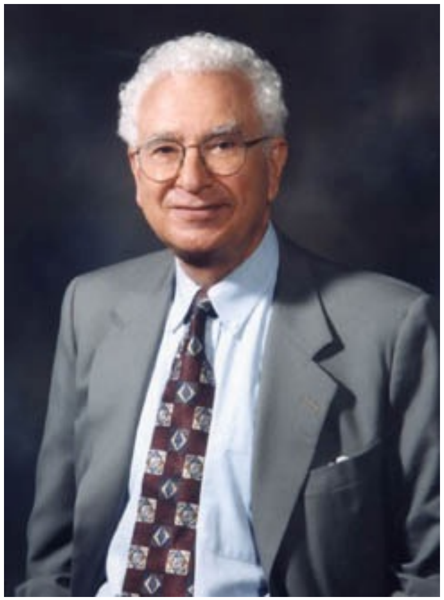
2-mile long linear accelerator

30 GeV

electrons

Quarks and anti-quarks ???

1964



Murray Gell-Mann

up
down

strange

mesons: $q\bar{q}$

baryons: qqq

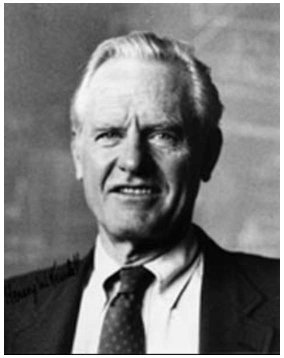
How quarks were discovered?
Who with who collision?
How quarks were named?

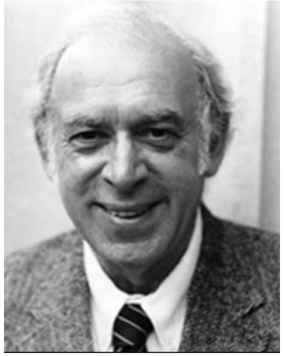
http://hyperphysics.gsu.edu/hbase/Particles/quark.html#c1

Inside the Proton

1968

SLAC - MIT Group

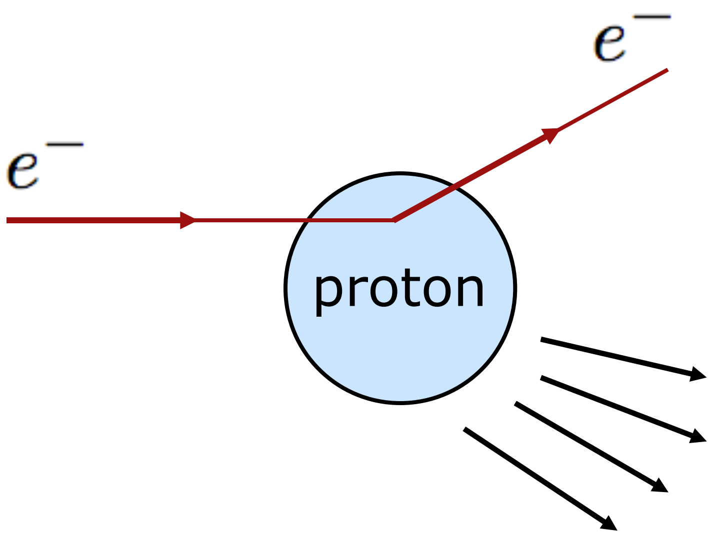

Kendall

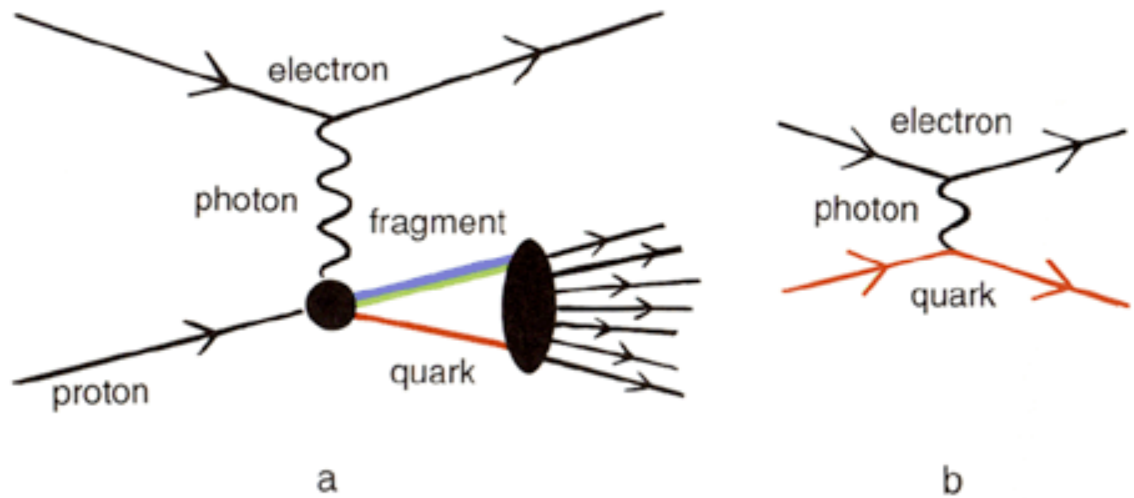

Friedman

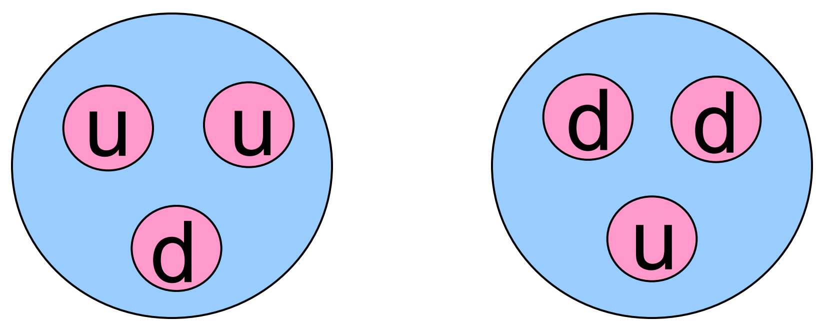

Taylor

Rutherford scattering off of a point objects again -deep inelastic scattering

Inside the Proton







proton neutron

Fundamental Particle Physics by ...

1974

			gauge boson
leptons	ν_e	ν_μ	γ
	e^-	μ^-	
quarks	u		
	d	s	

Compare with 1932 classification

The Golden Period

1974 – 1982

Discovery of a New Quark

1974 SPEAR –

Berkeley ?

Stanford group ?

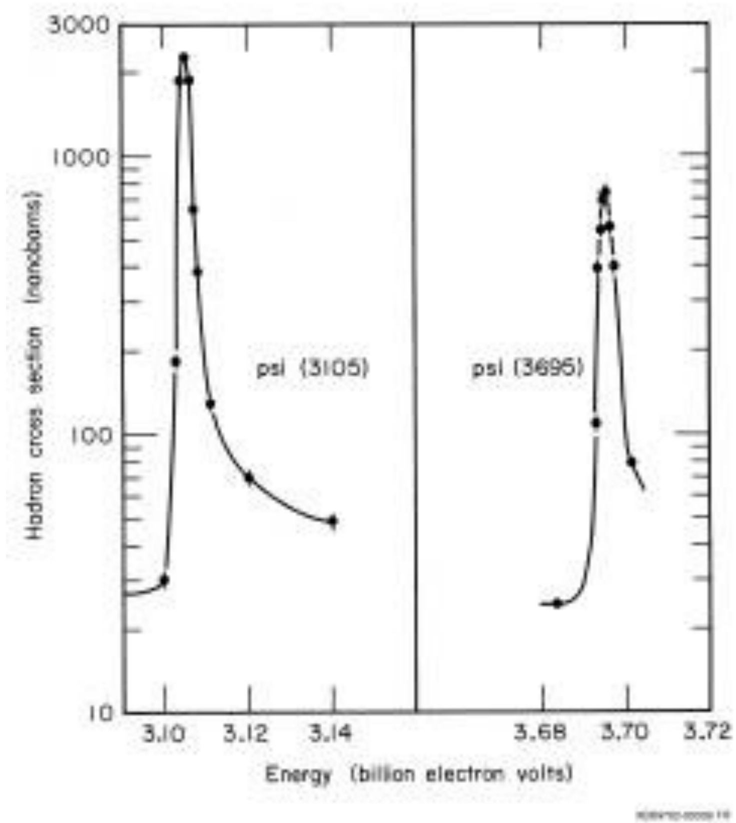
Electron-positron collision at 3GeV

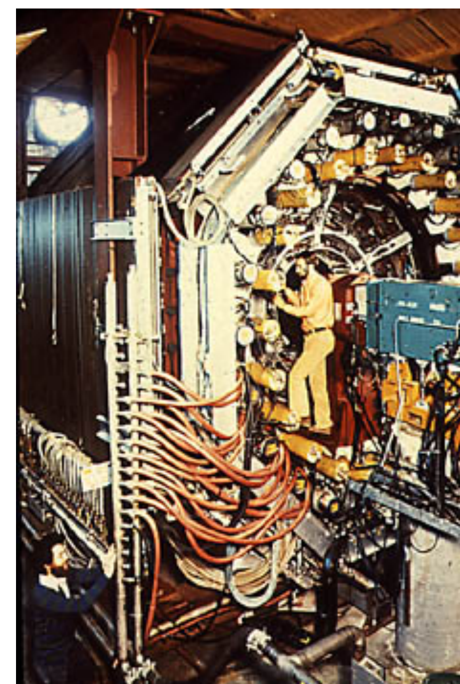
J-psi meson

$$e^+e^- \to J/\psi$$

Discovery of a New Quark

Burt Richter
@ Stanford



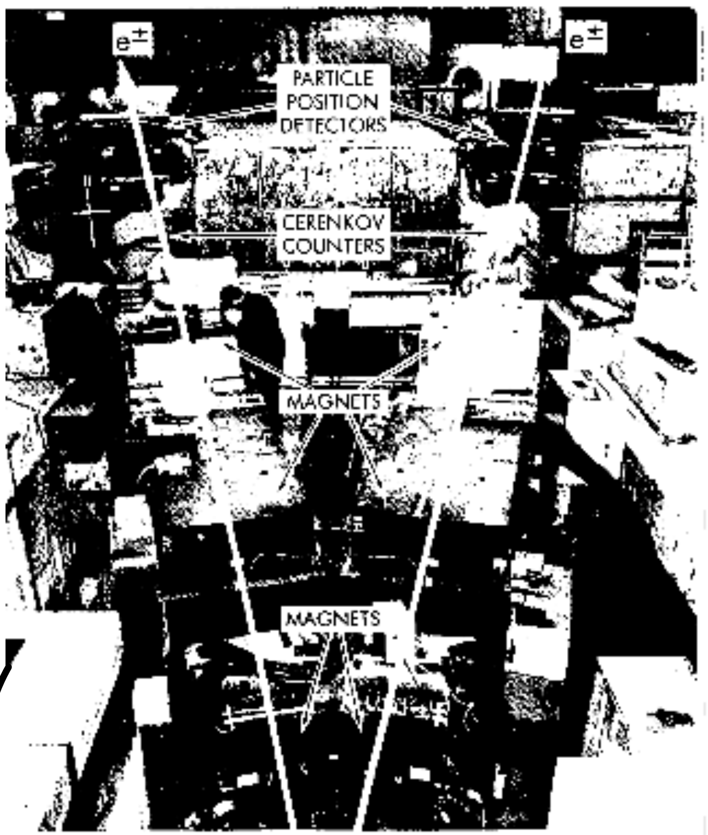


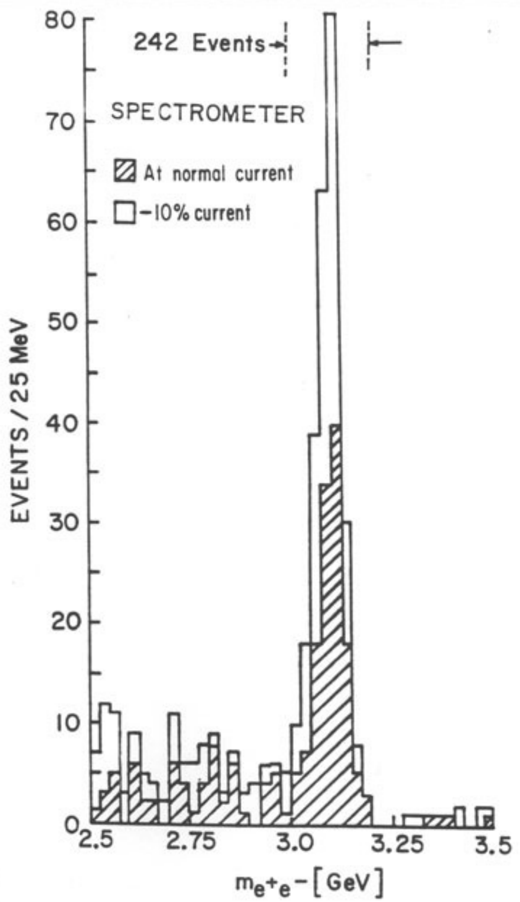
bound state of charm and anti-charm quarks.
Charmonium !

$$J/\psi$$

Simultaneous Discovery

$$p\,p \rightarrow J/\psi + X$$





Sam Chao Ting
@ Brookhaven

AGS-experiment
Proton-proton
Collision, at 33GeV

Double-arm spectrometer

physics, US politics and money

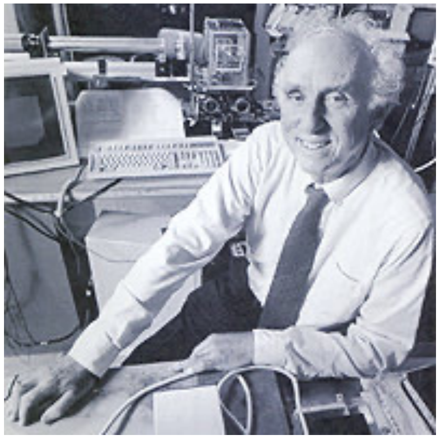
1990, Waxahachie, south of Dallas, Texas

- Superconducting Super Collider (SSC), 87.1 km circumference, 20 TeV/proton x2
- Aprox 7 billion dollars
- cancelled in 1993

Discovery of a New Heavy Electron

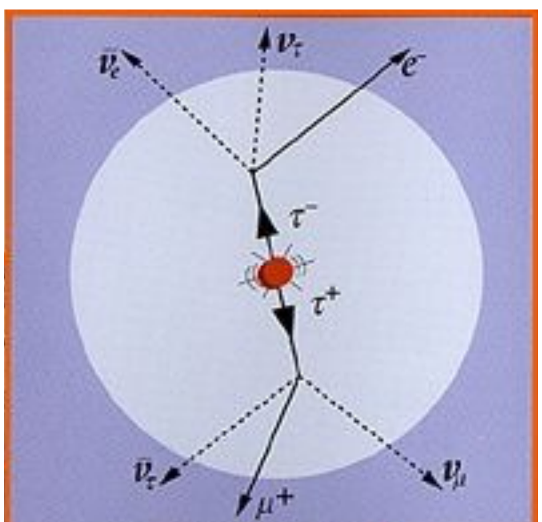
1975

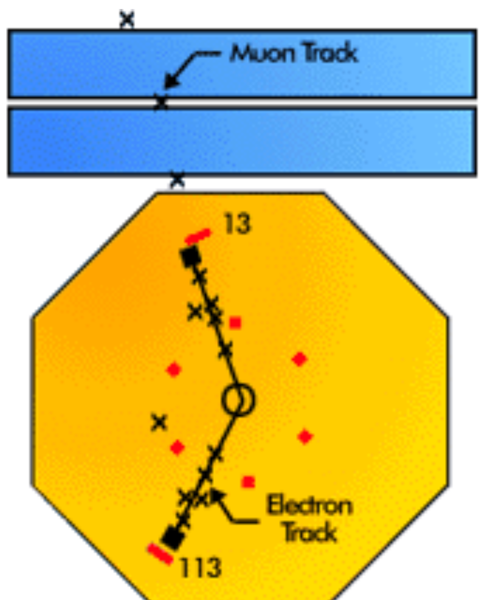
$$e^+ e^- \rightarrow \tau^+ \tau^-$$
$$\rightarrow \mu^+ e^- \nu_\tau \bar{\nu}_\tau \bar{\nu}_\mu \bar{\nu}_e$$



Martin Perl

Electron-positron collision at ~3GeV





Tau lepton (just like electron except about 2000 times more massive.

Fermilab

400 GeV Proton Synchrotron

2km (1.3mi) diameter ring

Robert Wilson

Discovery of Another New Quark

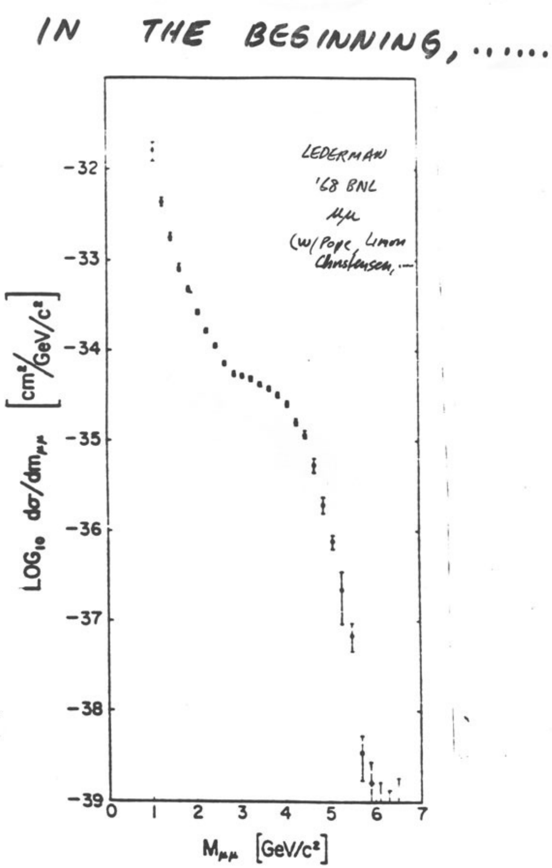
Leon Lederman

1976 Υ

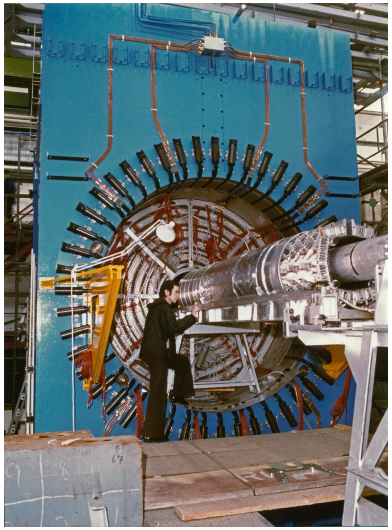
$$pp \rightarrow \Upsilon + X$$

$$\Upsilon \rightarrow \mu^+ \mu^-$$

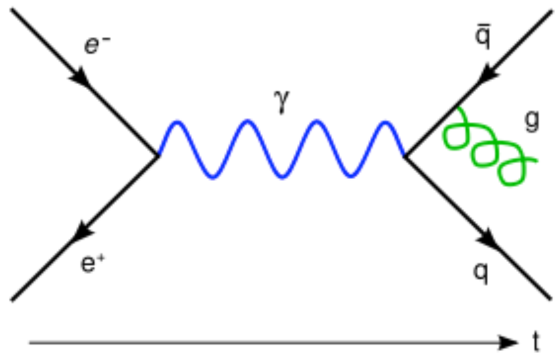
bound state of bottom and anti-bottom quarks



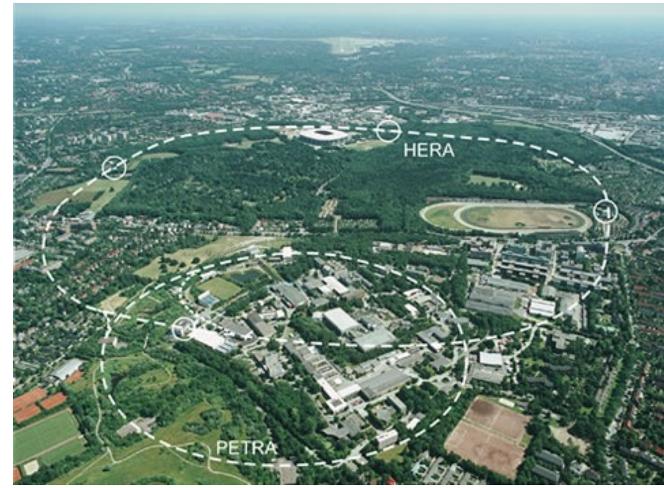
Discovery of the Gluon



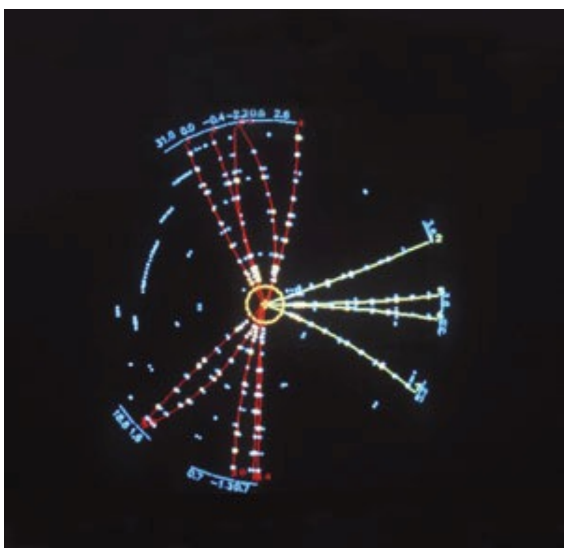
1979



30 GeV e^+e^- Collider

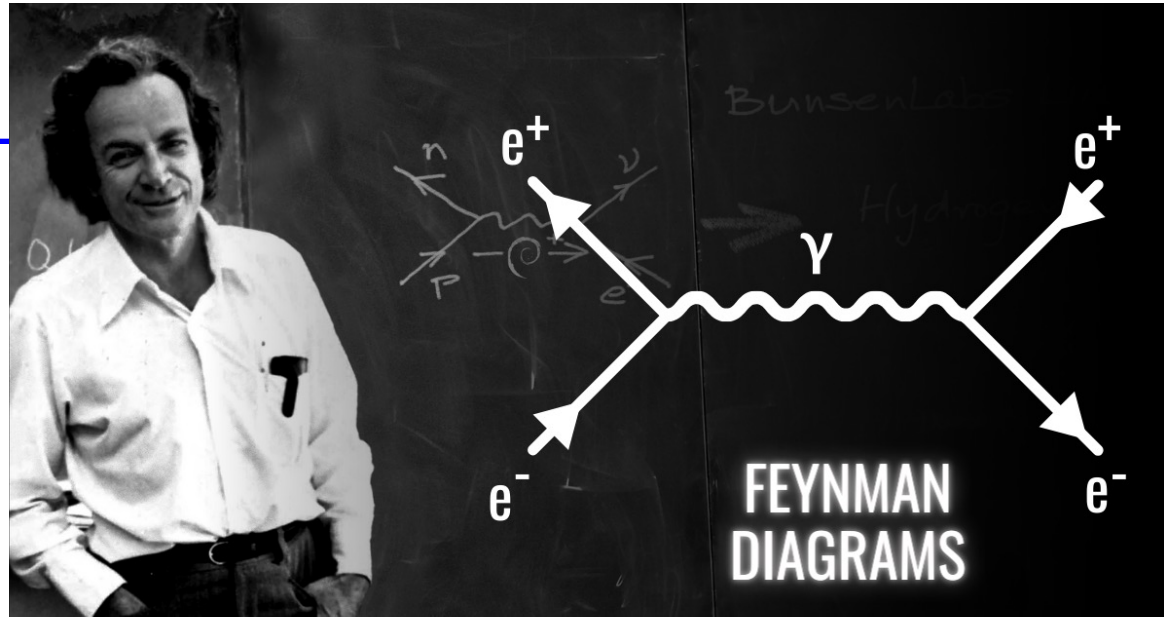


TASSO detector at DESY, PETRA-Positron Electron Tandem Ring Accelerator



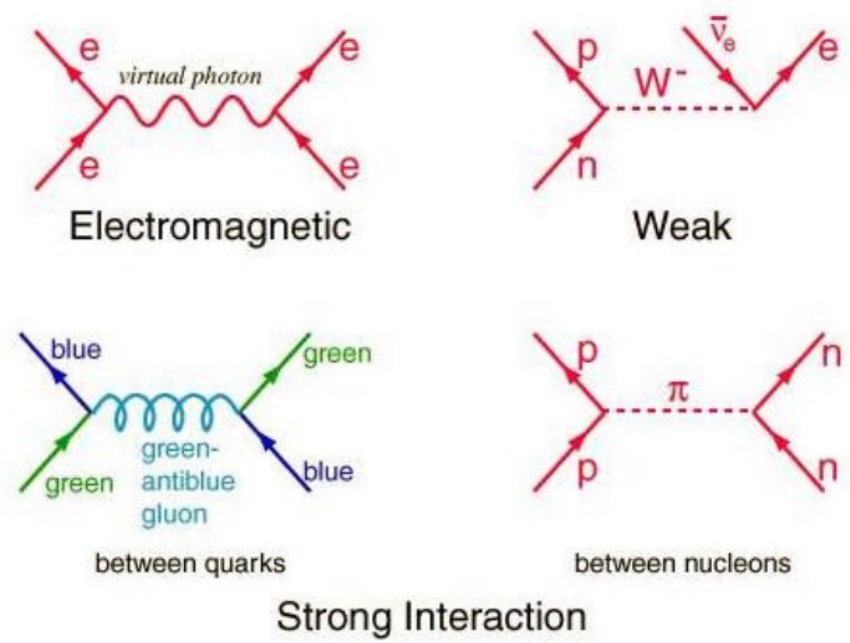
carrier of the strong force
Quantum Chromo Dynamics

binds quarks together
to make proton



Since 1948-a visual representation of particle interactions in quantum field theory.

-Squiggly, dotted, straight lines with arrows

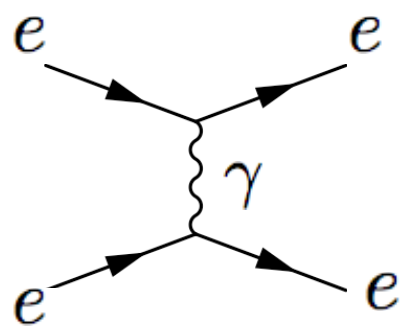


The Standard Model

Quantum Electrodynamics

charged particles interacting
by photon exchange

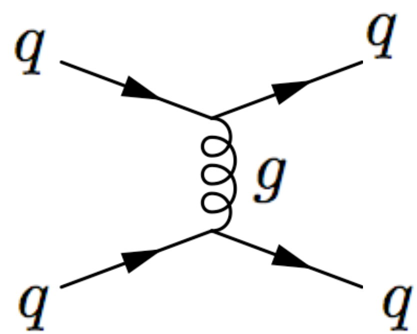
atomic physics



Quantum Chromodynamics

quarks interacting
by gluon exchange

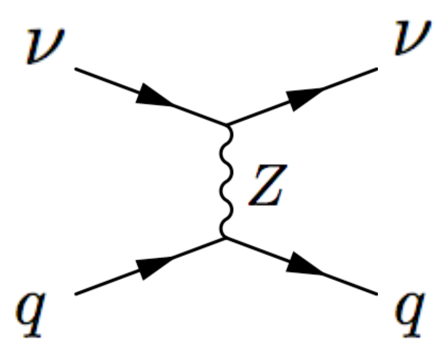
binding of quarks

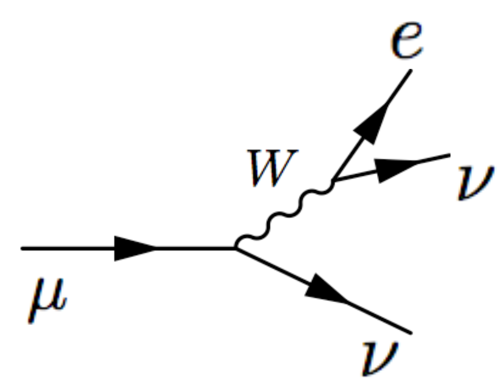


Weak Force

particles interacting
by W and Z exchange

heavy lepton decay
heavy quark decay
neutrino interactions





CERN

Off to the French Alps

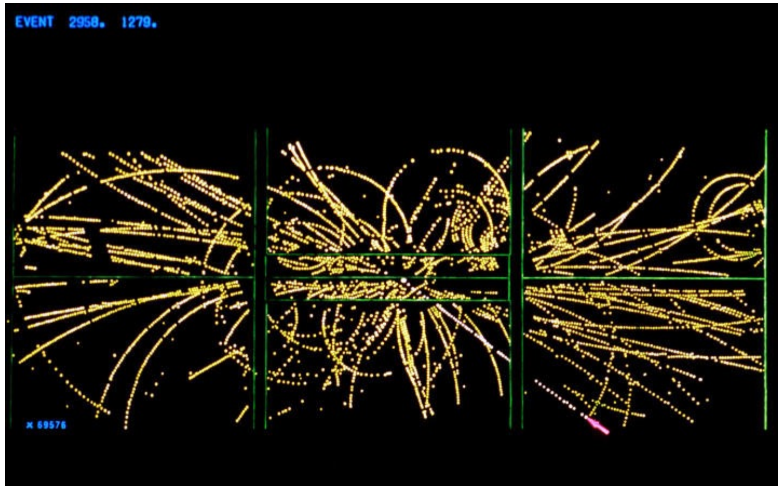
proton – antiproton

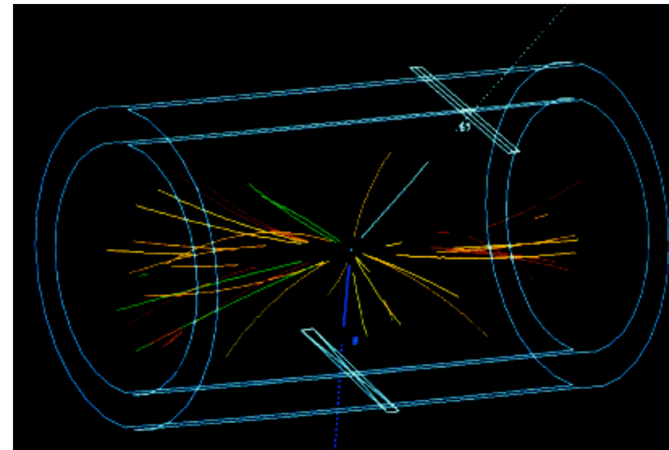
collisions at 450 GeV

Discovery of the W and Z bosons

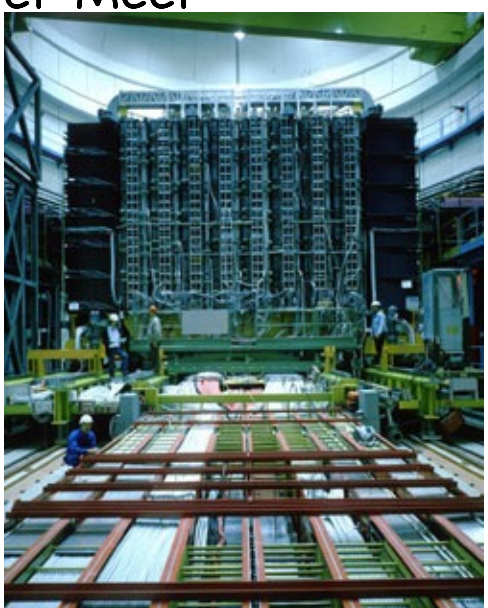
1982

Rubbia and van der Meer

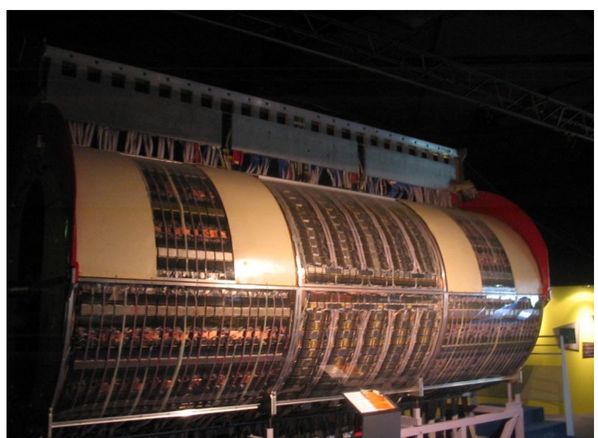


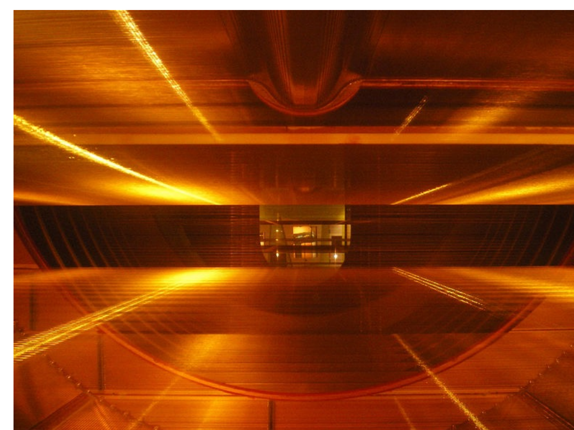


$$W \rightarrow e\,\nu \qquad Z \rightarrow e^{+}e^{-}$$



UA 1 Detector





1982: The Standard Model

leptons	ν_e	ν_μ		
	e^-	μ^-	τ^-	
quarks	u	c		
	d	s	b	

gauge bosons

γ

g

W^+ W^- Z^0

The Recent Period

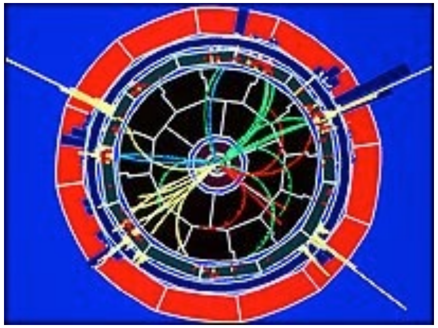
1982 – 2012

Large Electron-Positron (LEP)

1989 - 2000

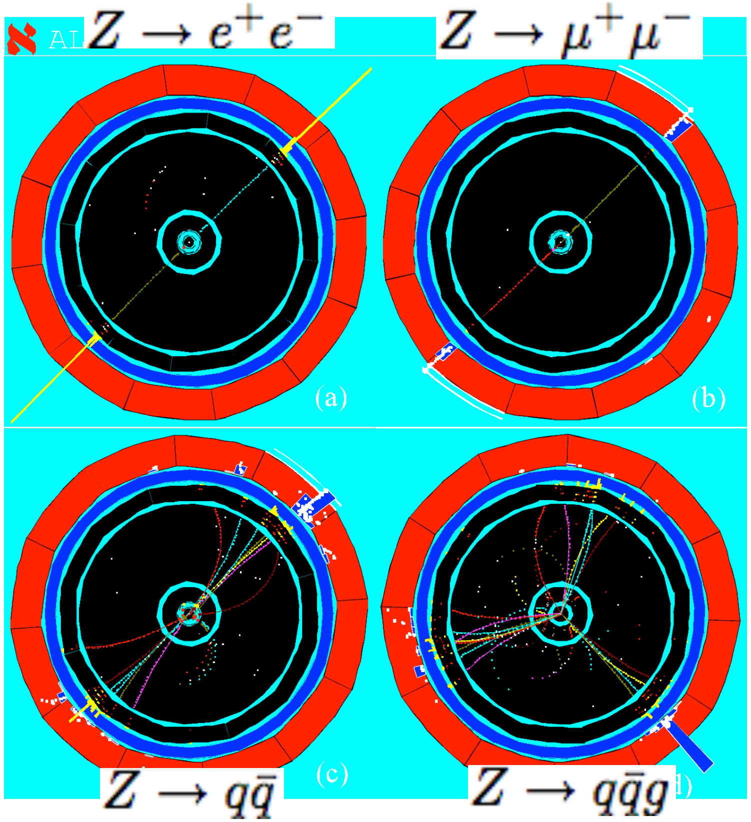
100 GeV electron - positron collisions at CERN

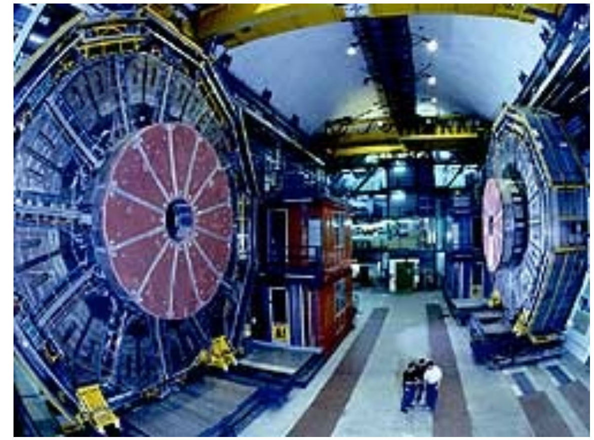
27 kilometer tunnel



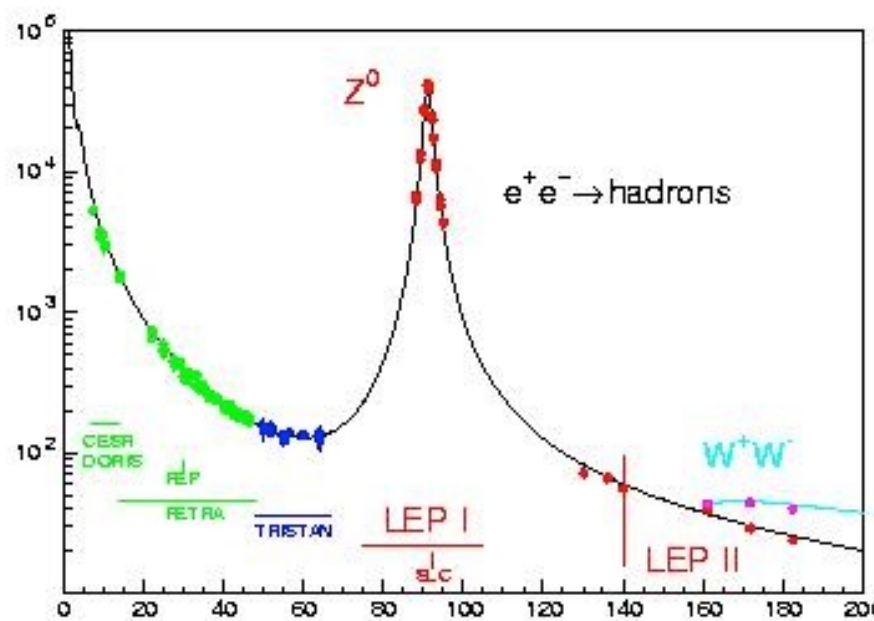
Z Factory

Over 10 million Z's produced and decays studied by four large detectors





Aleph Detector



Precision Tests of Standard Model

- Standard Model tested to 0.1% level
  in agreement with all measurements
  down to 10^{-16} cm

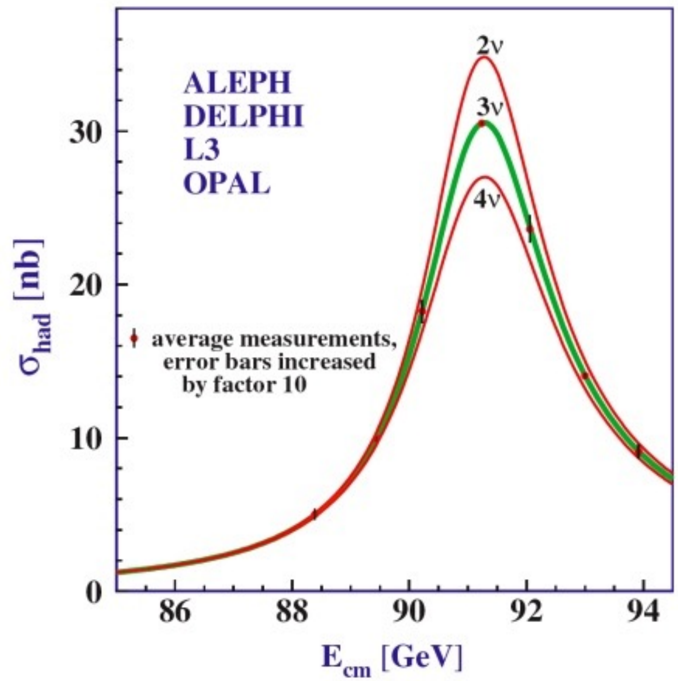
- Only three light neutrinos

$$Z \longrightarrow \nu\bar{\nu}$$

- Higgs still missing

$$e^+e^- \longrightarrow ZH$$

$$m_H c^2 > 114 \text{ GeV}$$



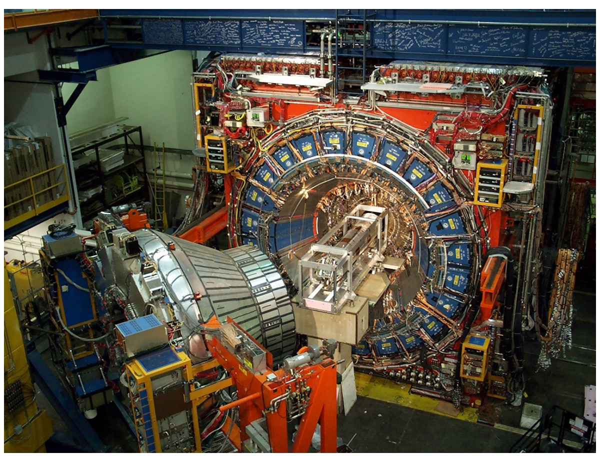
Discovery of the Top Quark

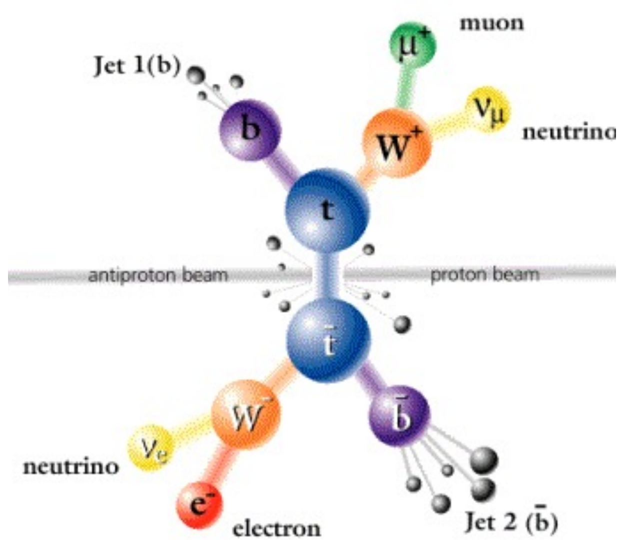
1995 2 TeV Proton - Antiproton collisions

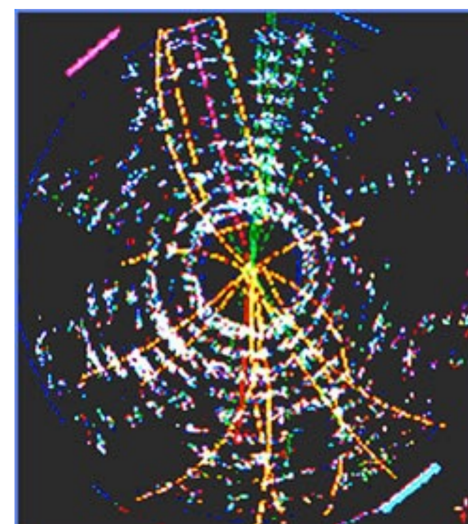
D0 Collaboration

Fermilab Tevatron Collider

Production top anti-top







Fundamental Particle Physics

20012

leptons

$\nu_e \quad \nu_\mu \quad \nu_\tau$

$e^- \quad \mu^- \quad \tau^-$

quarks

$u \quad c \quad t$

$d \quad s \quad b$

gauge bosons

γ

g

$W^+ \quad W^- \quad Z^0$

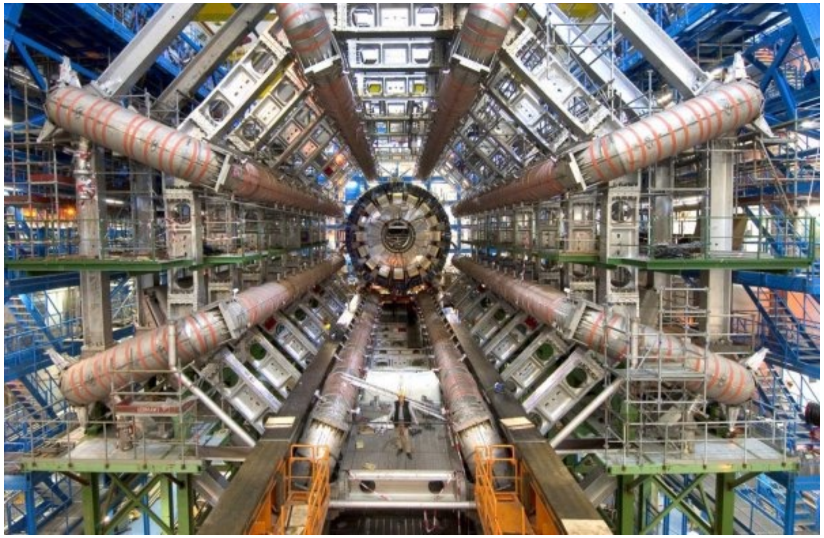
Higgs

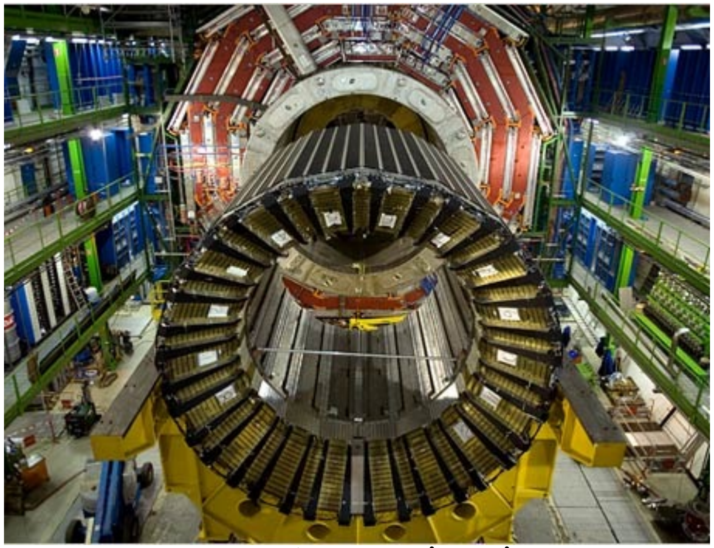
The Large Hadron Collider

2012

14 TeV proton antiproton collisions in the LEP tunnel

probing matter at the 10^{-17} cm scale


Atlas Detector


CMS Detector

6 min

Large Hadron Collider - Animation Video

https://www.youtube.com/watch?v=FLrEghnKncA

Summary

Complete, consistent theory of fundamental physics

- Fundamental constituents:

  6 quarks and 6 leptons
  plus antiparticles

- Three fundamental forces:

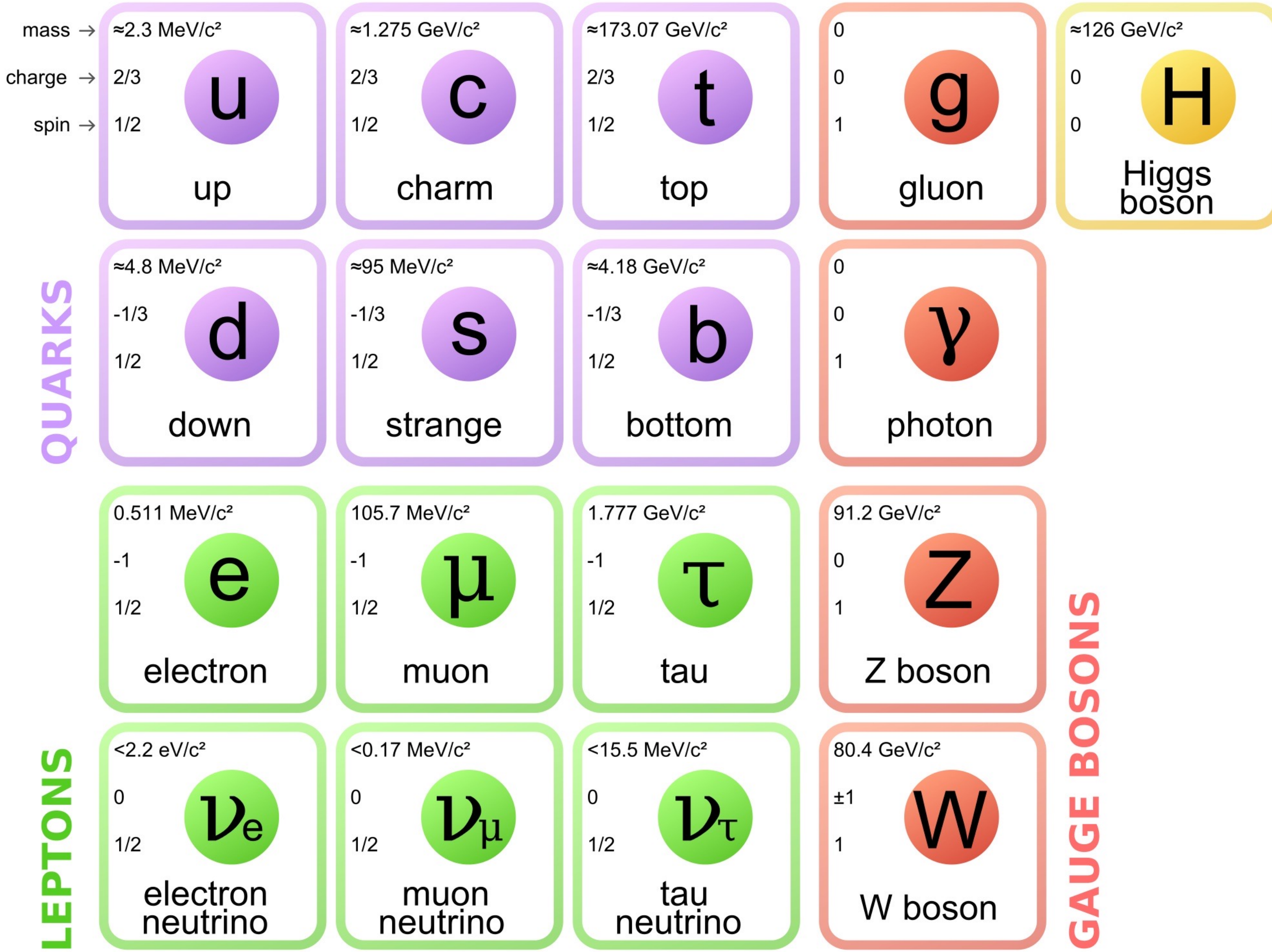
  Electromagnetic mediated by photons

  Strong mediated by gluons

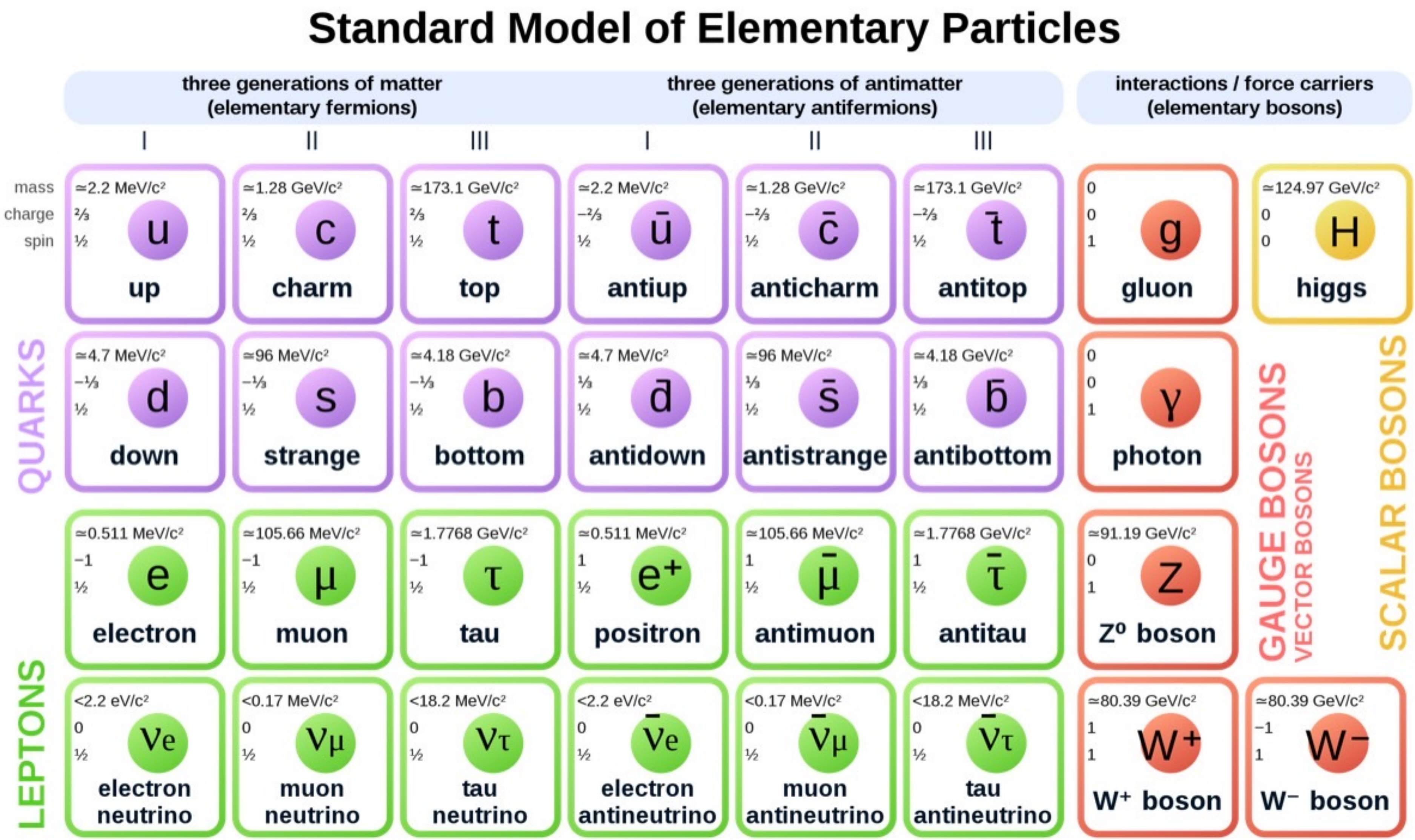
  Weak mediated by W^+ W^- Z^0

- Agrees with all experiments to 10^{-16} cm

- Higgs particle


mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
QUARKS
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
LEPTONS
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
GAUGE BOSONS

As of now, 2024, this is it …



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

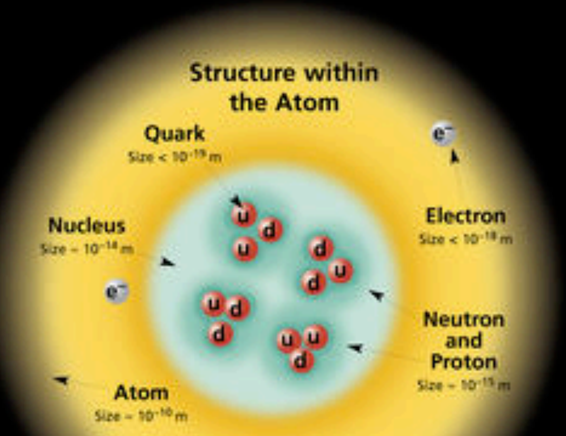
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

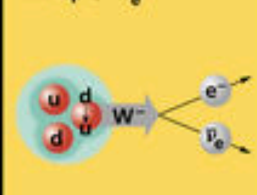
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

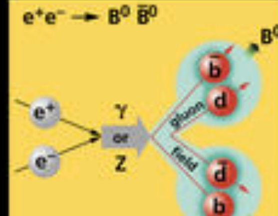
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



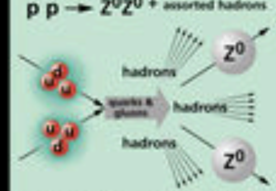
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
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