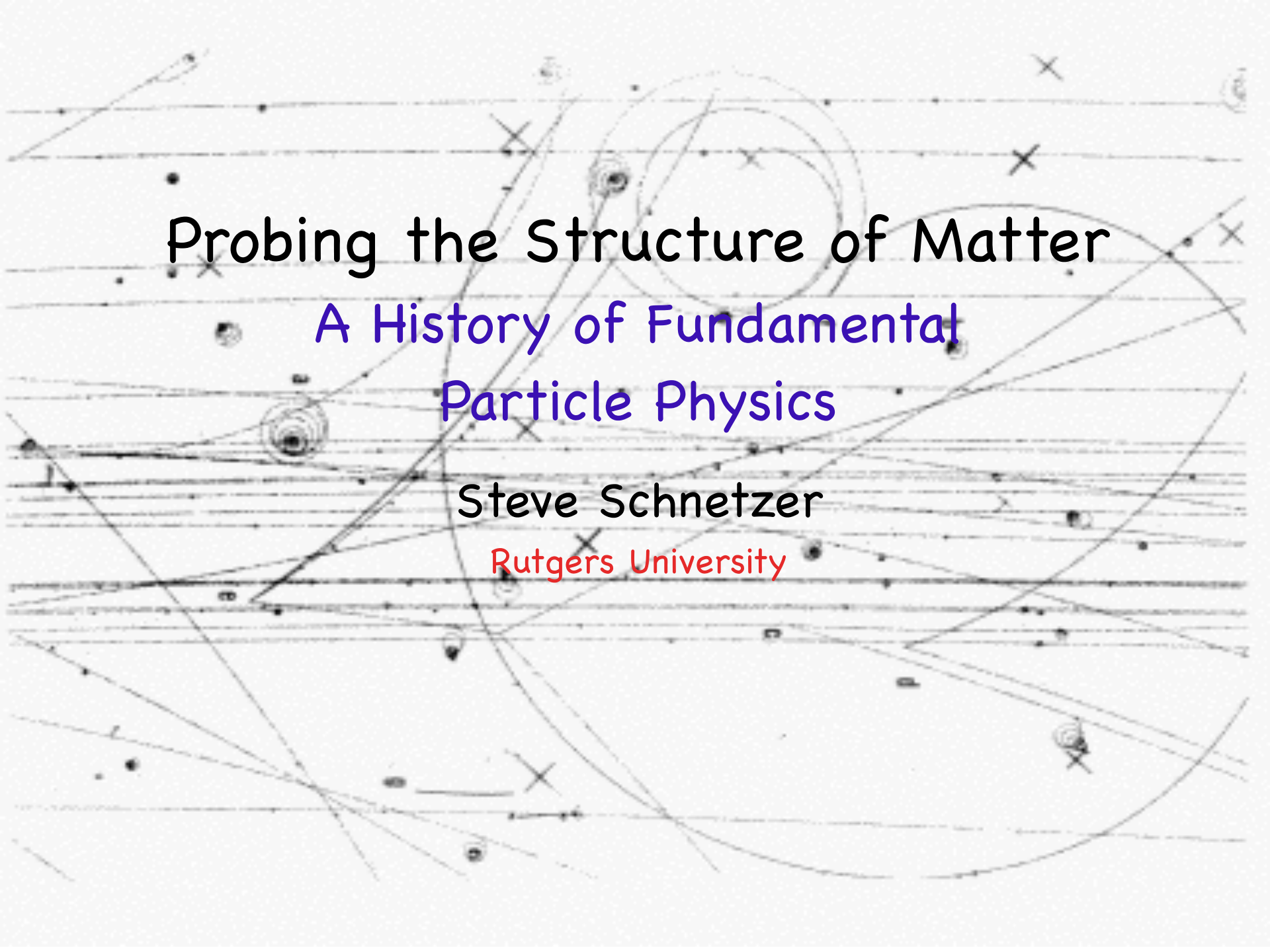


Probing the Structure of Matter

A History of Fundamental Particle Physics

Steve Schnetzer

Rutgers University

Fundamental Particle Physics

Fundamental Particle Physics

- What are the fundamental constituents of the universe?

Fundamental Particle Physics

- What are the fundamental constituents of the universe?

- How do they interact with each other?

How to Judge How We're Doing

Constituents

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

Theory

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

Ancient Greece

Plato

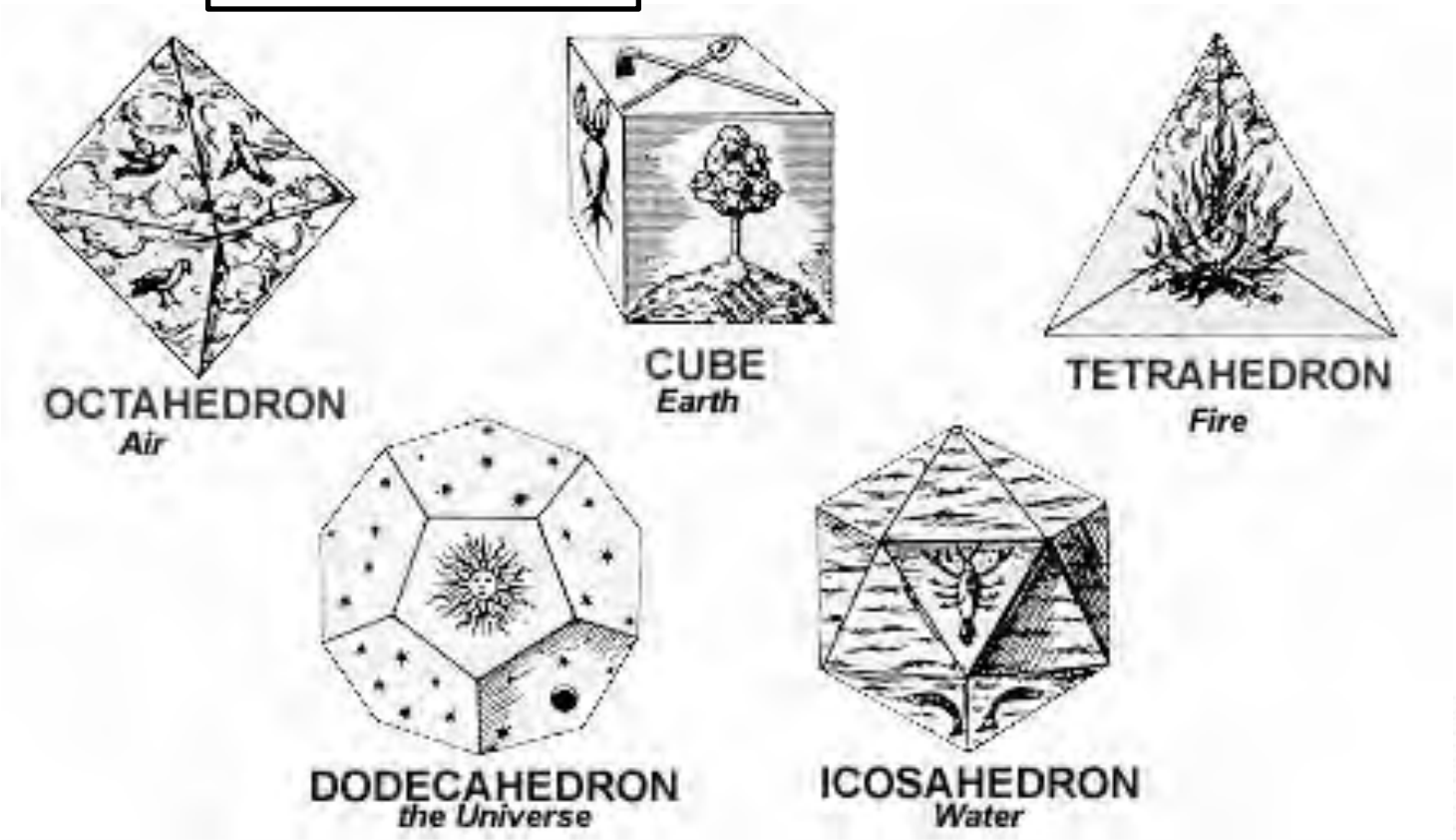
Aristotle

Ancient Greece

Ancient Greece

Fundamental Physics

Circa 500 B.C.

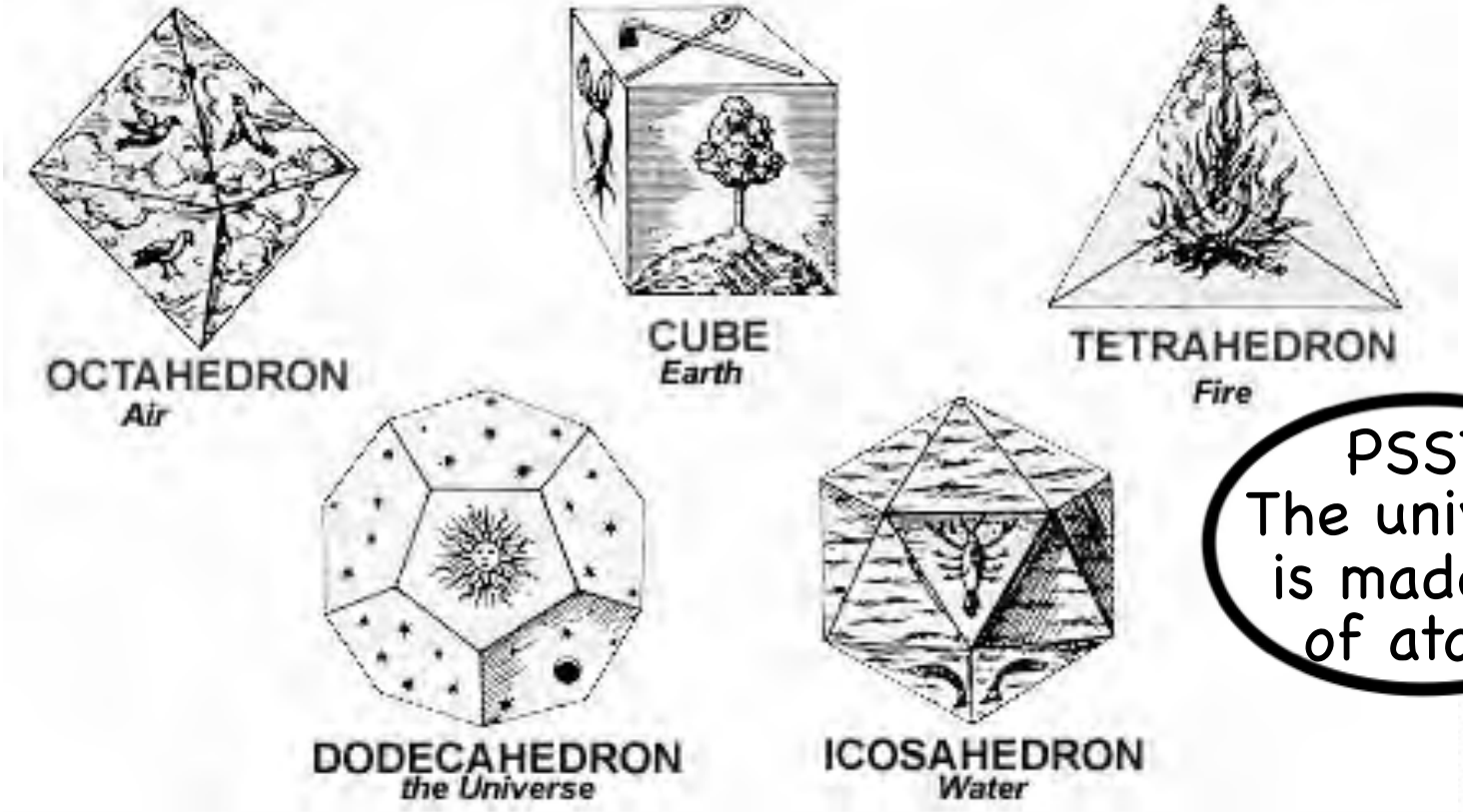


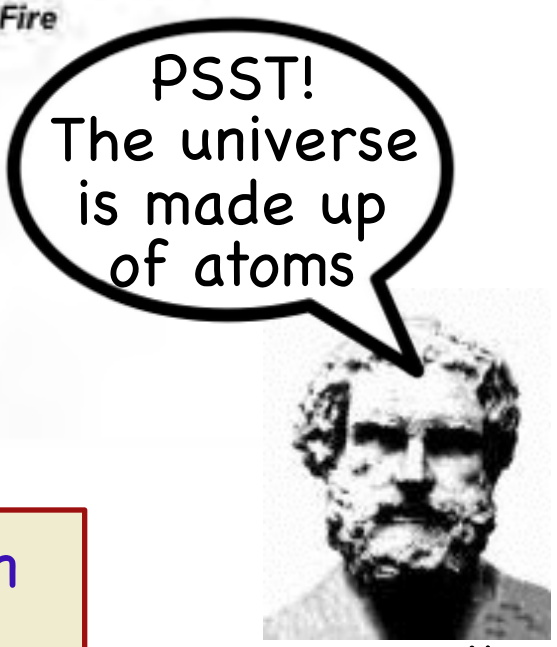
The universe is built on the five Platonic solids

Democritus

Fundamental Physics

Circa 500 B.C.





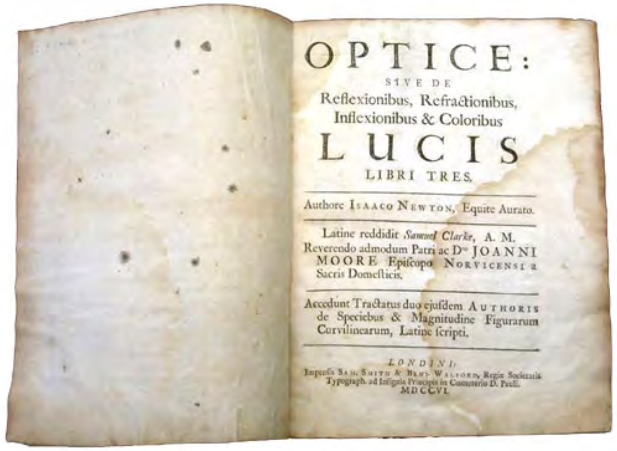
Democritus

The universe is built on the five Platonic solids

The Classical Period

1687 – 1897

Newton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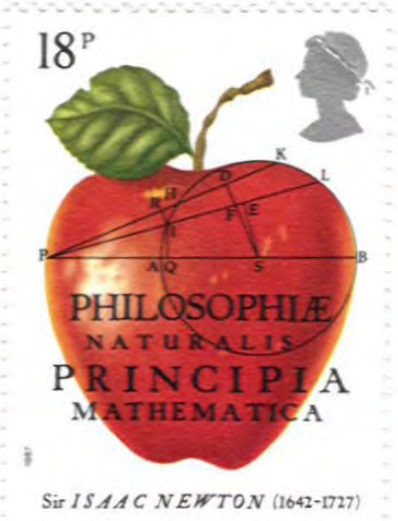
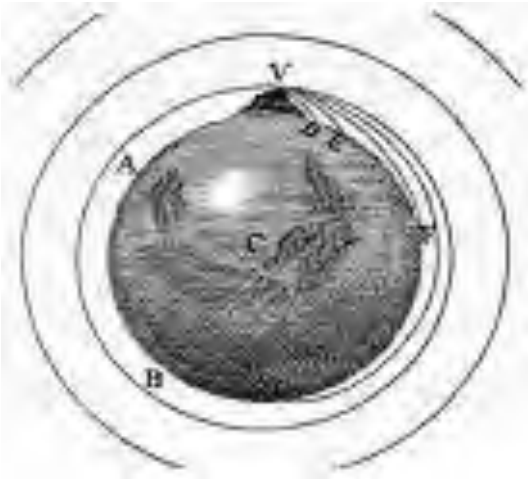
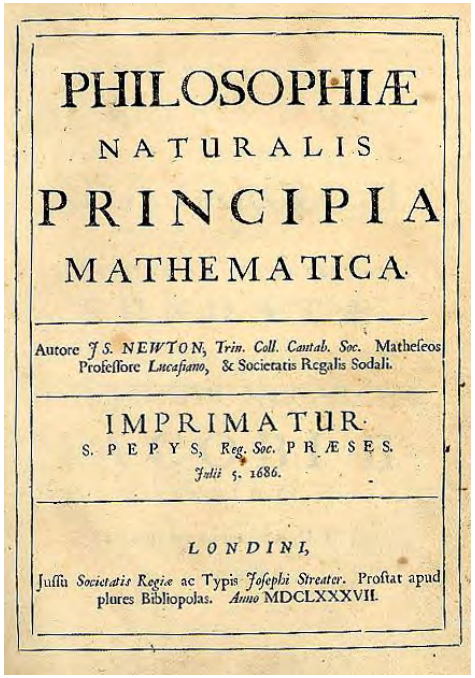
$$F = ma$$



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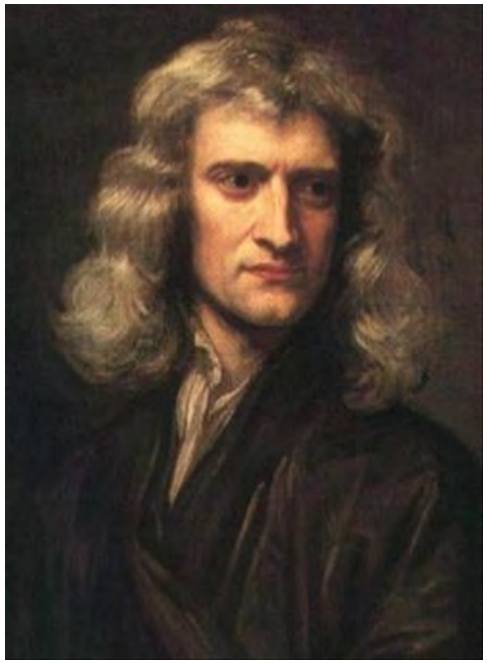
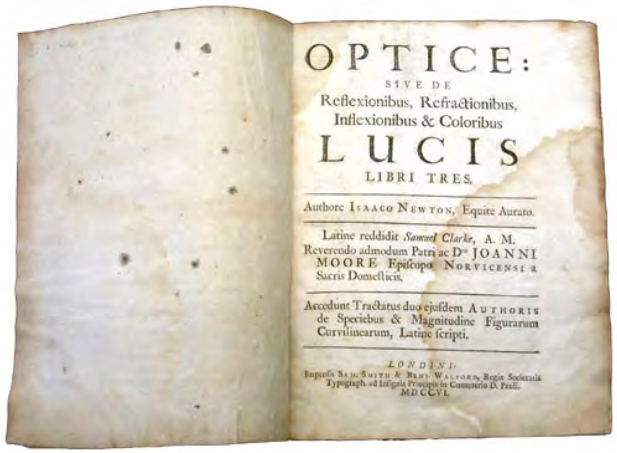


Newton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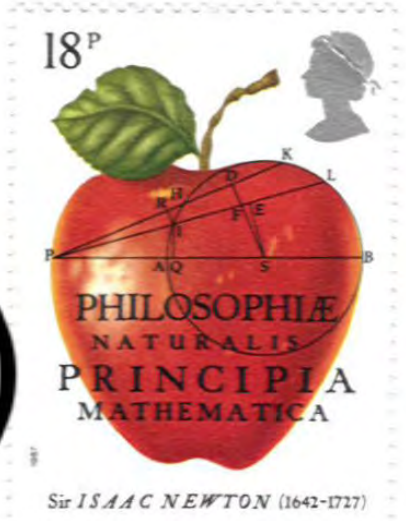
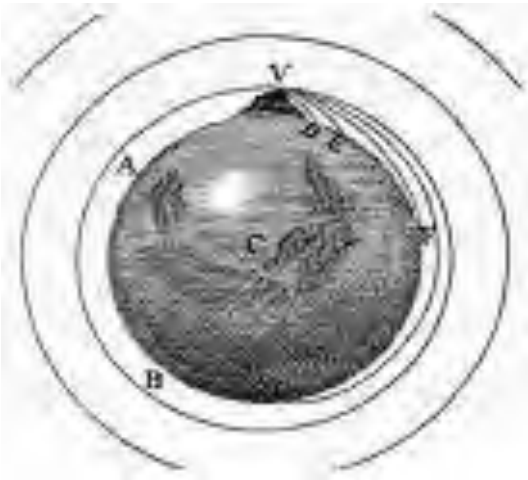
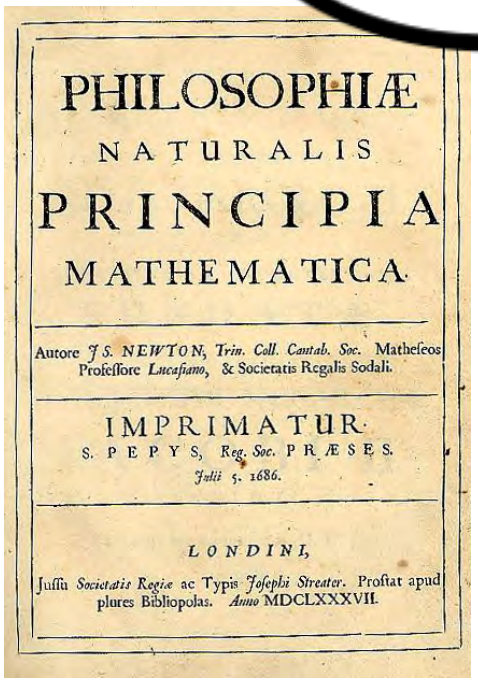
MDCCVI.

$F = ma$

The world is made of point particles



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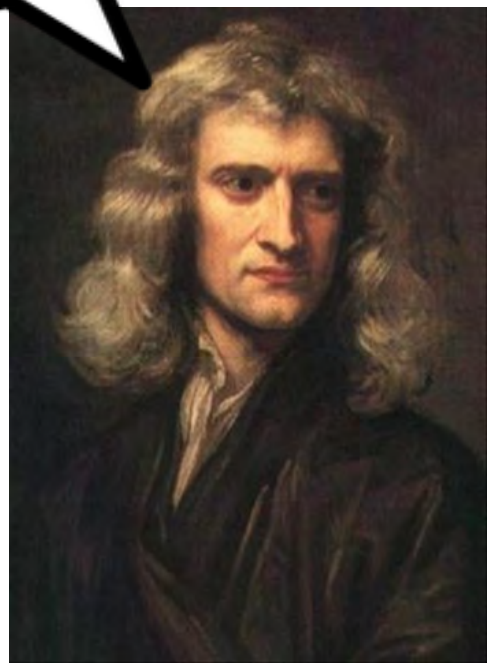
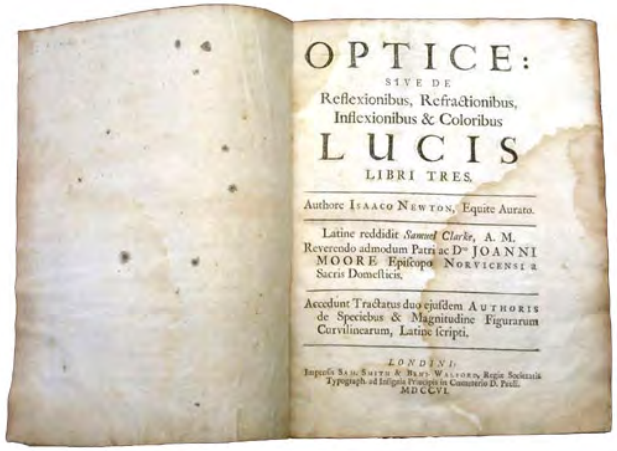


Newton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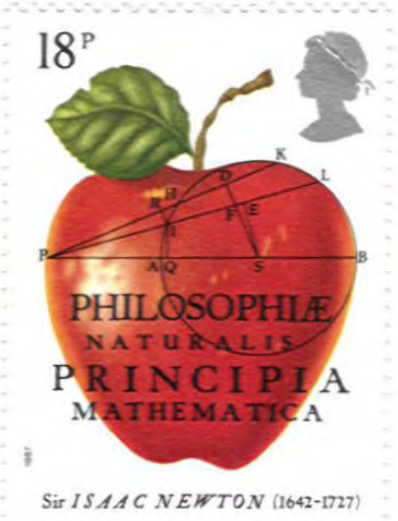

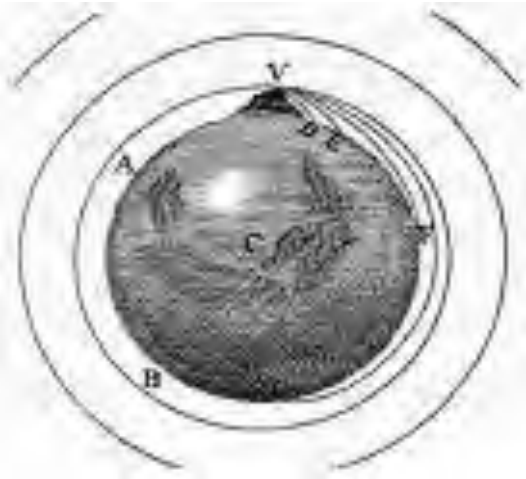

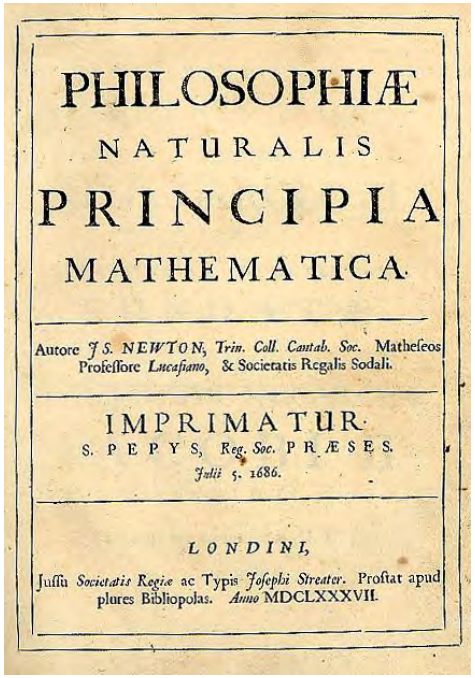
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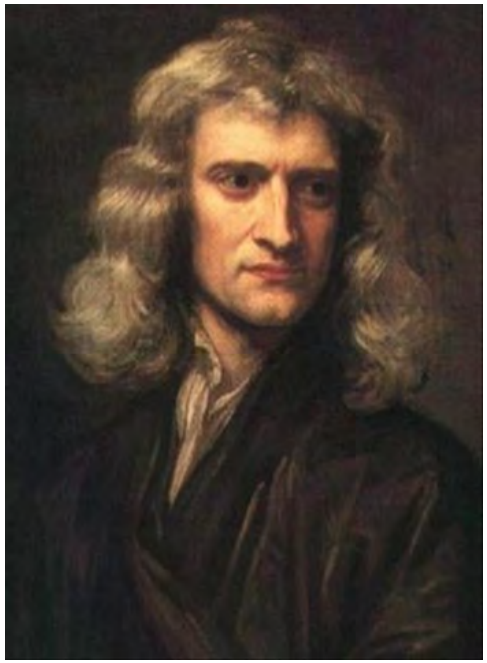
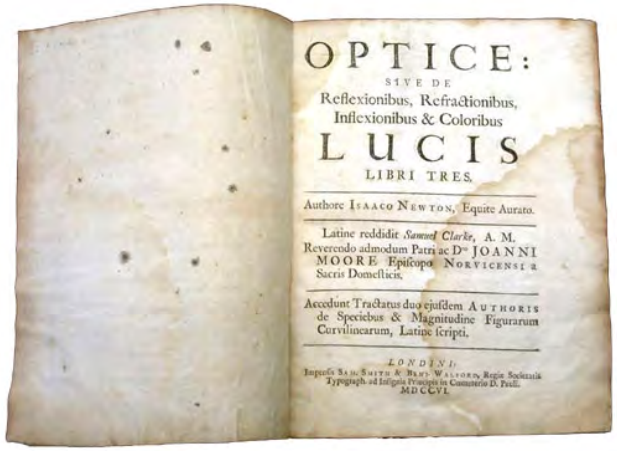


Newton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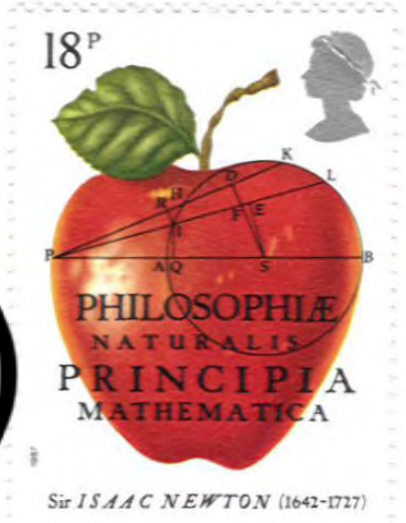
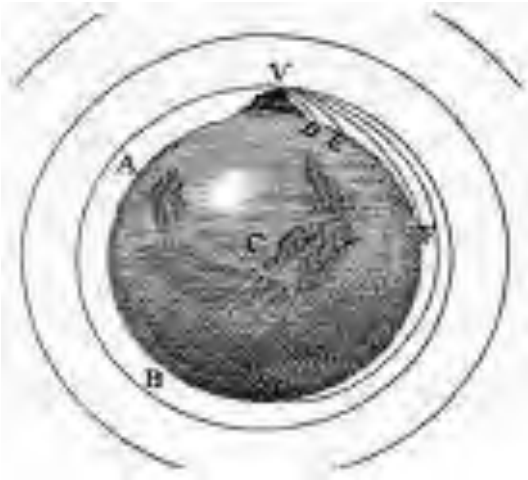
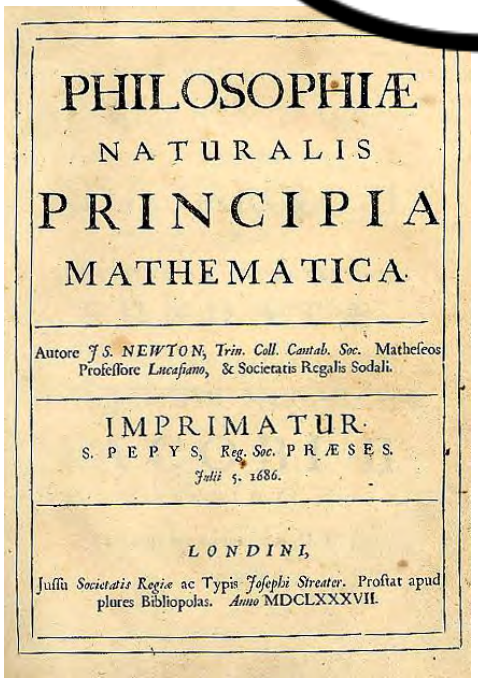
$$F = ma$$

I have no idea what they are



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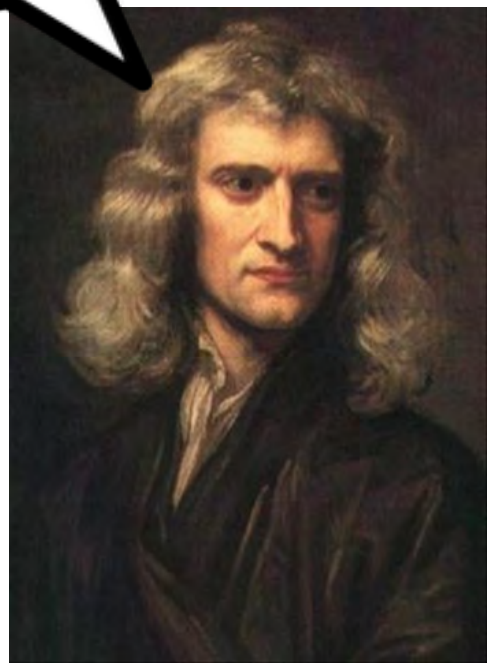


Chemists Discover Evidence for Atoms

1802

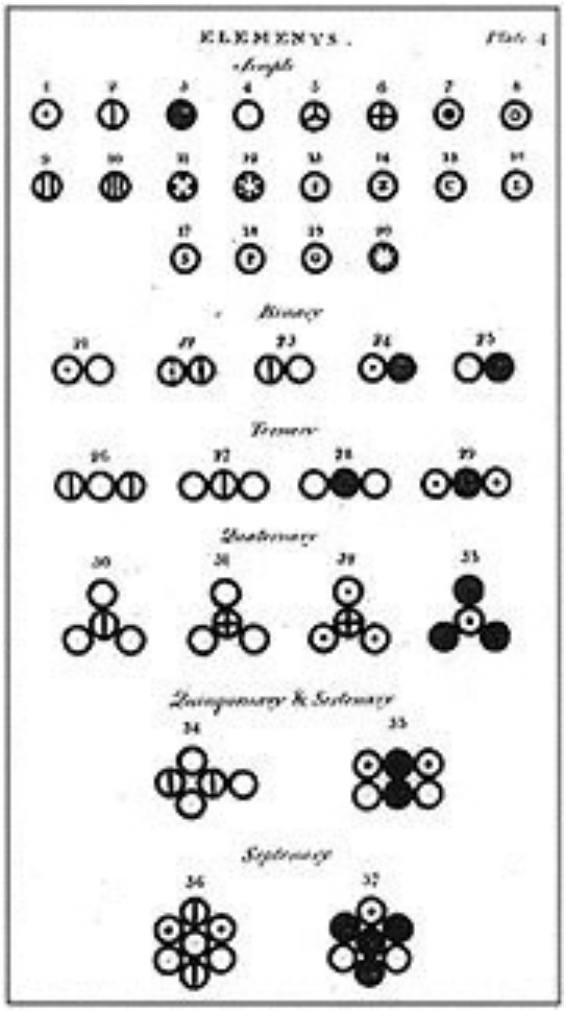
John Dalton

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

Discovered Brownian Motion

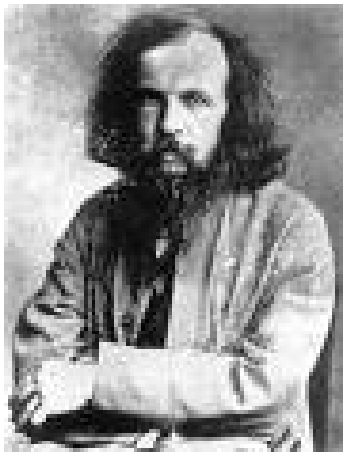
Robert Brown

Botanist

movie

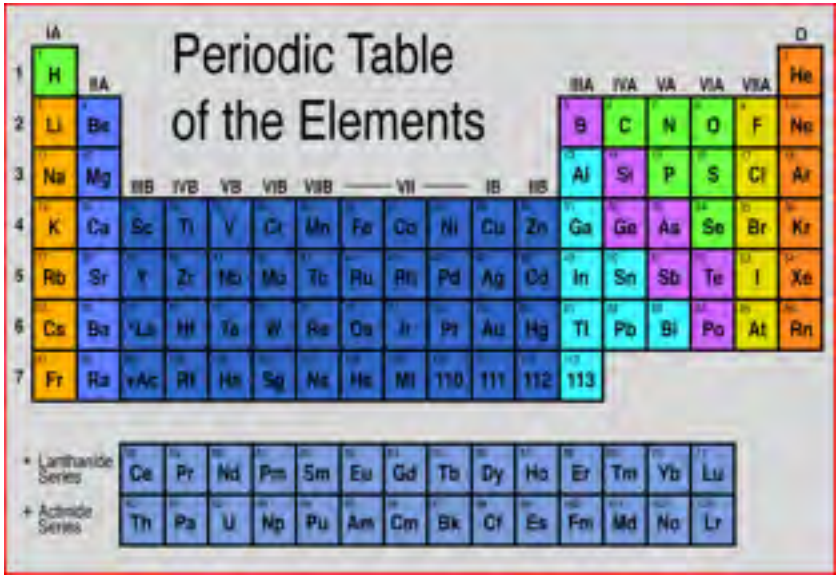
Periodic Table

1869



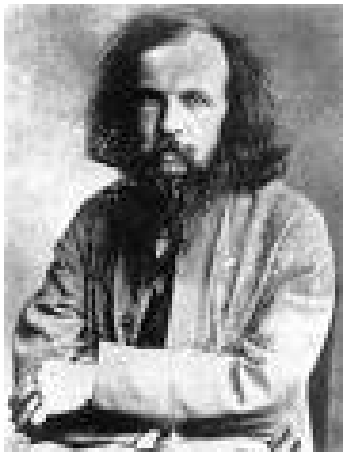
Mendeleev

a classification scheme

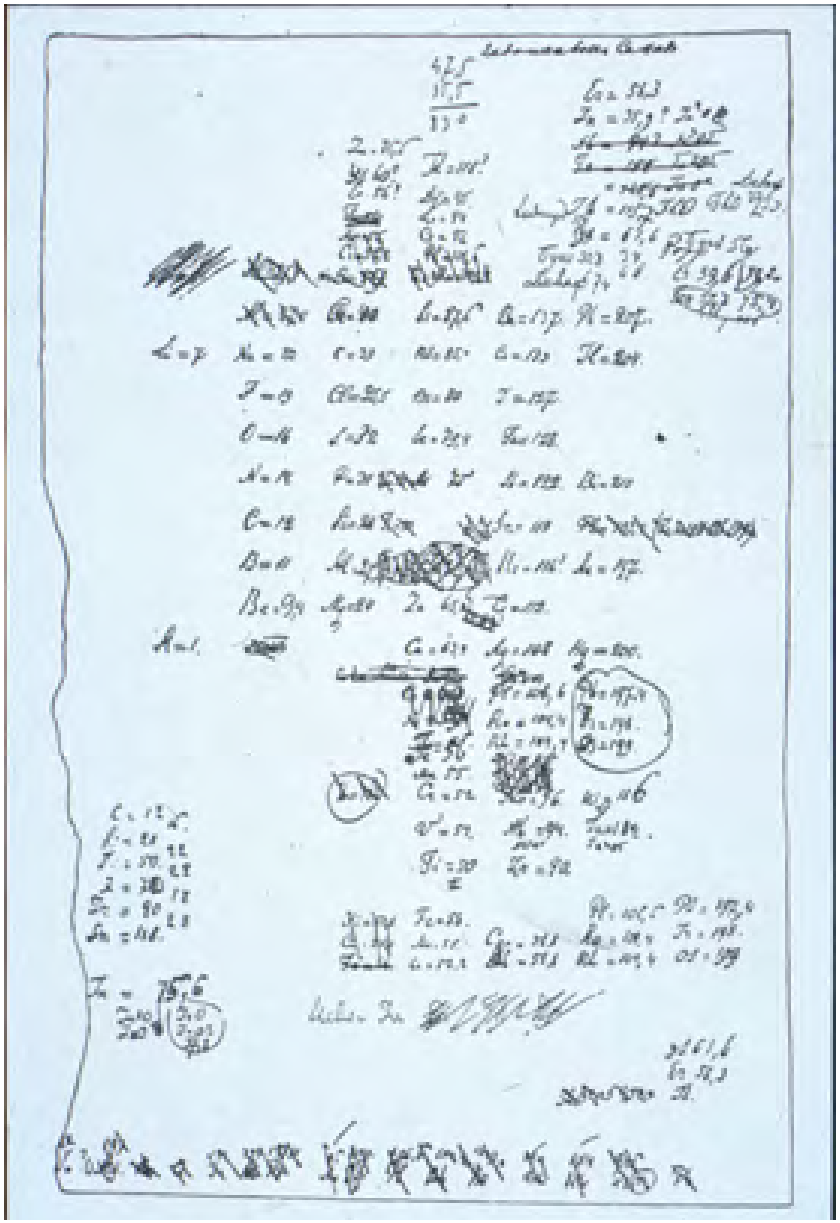


Periodic Table

1869



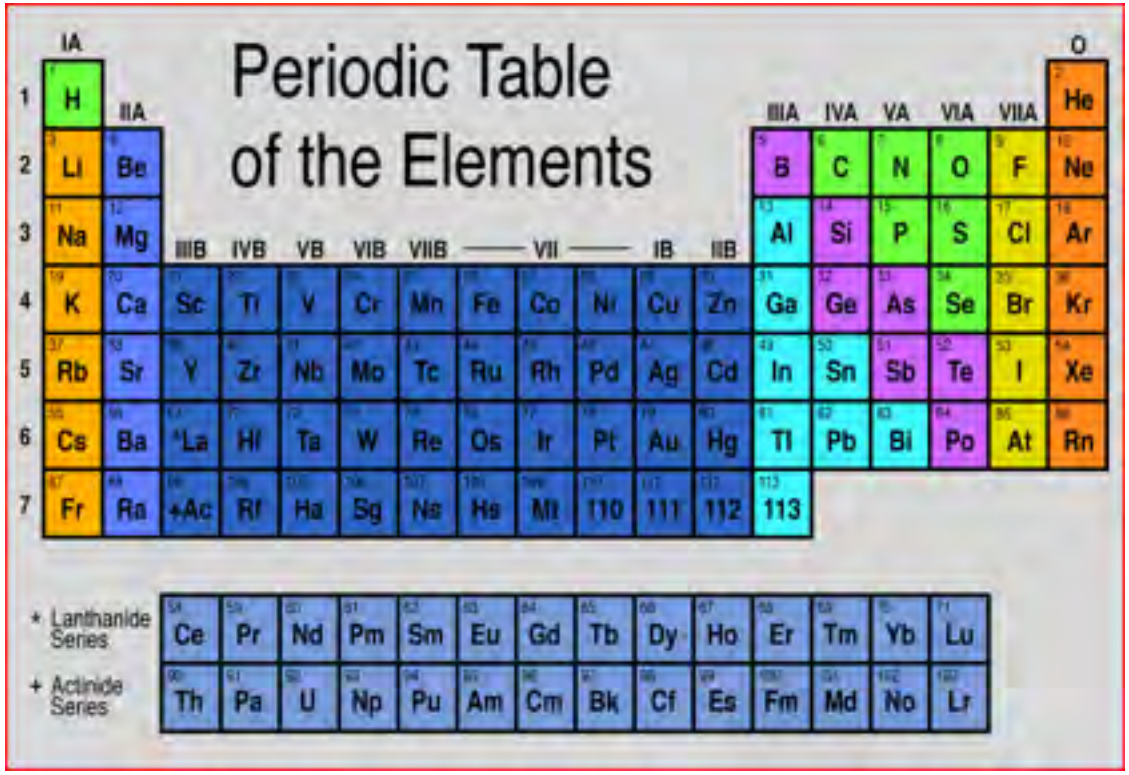
Mendeleev



Fundamental Particle Physics

End of 19th century

92 Atoms



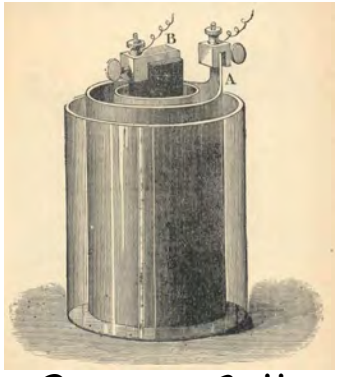
The Romantic Period

1897 –1932

The Cavendish

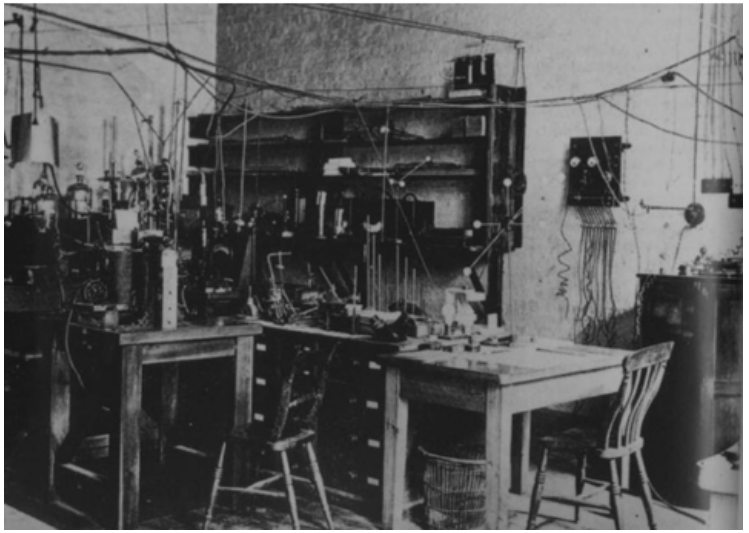
World's premier physics laboratory late 19th century

Cambridge University



Bunsen Cell

The Cavendish



A Typical Lab

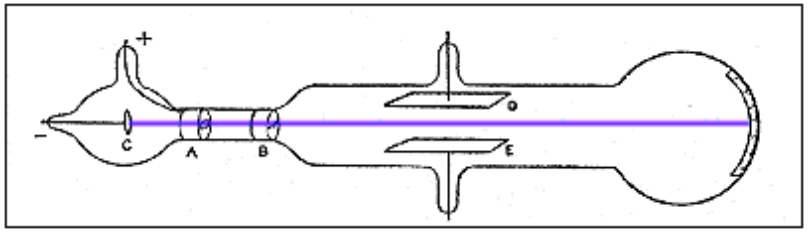
Discovery of the Electron

J. J. Thomson

Thomson's CRT

A new particle

electrically charged



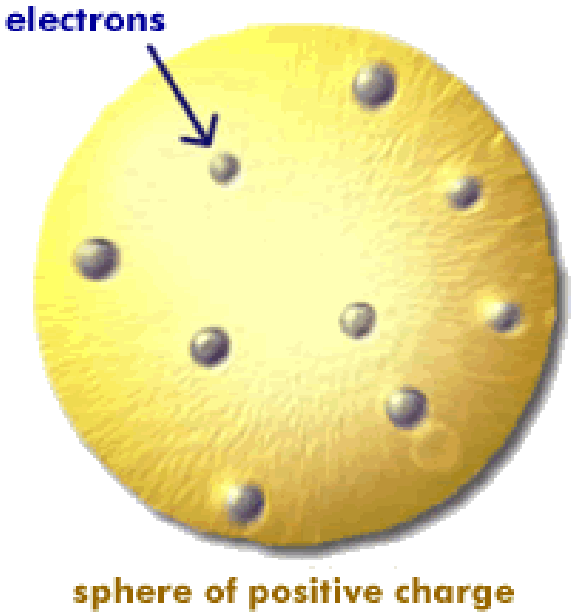
The Plum Pudding Model

can knock electrons out of atoms (photoelectric effect)

$\Rightarrow$ electrons are a part of atoms

How to make a stable
electrically neutral atom?

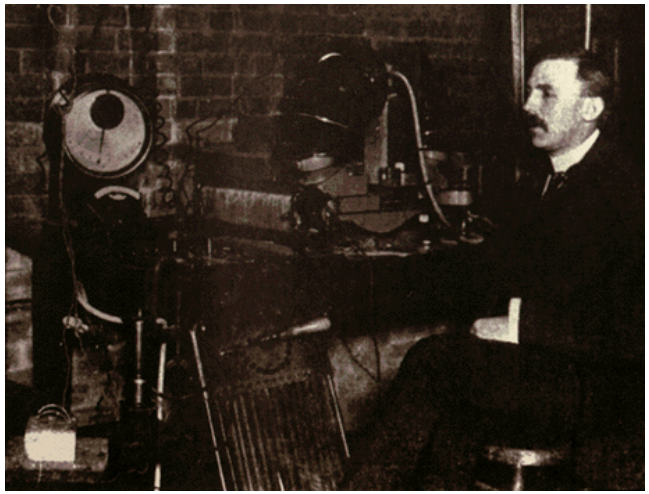
negatively charged electrons
distributed like raisins in a
positively charged "pudding"



Lord Rutherford

World's first high energy physicist

1910

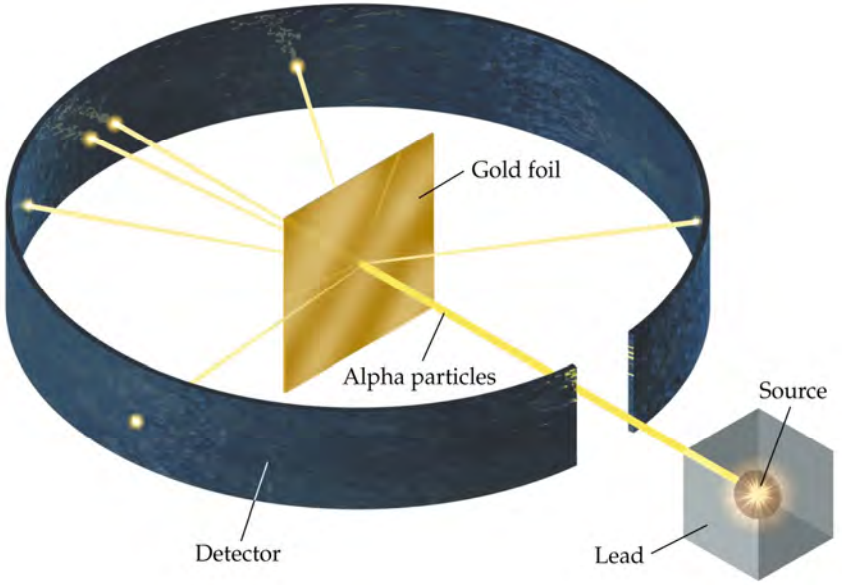


Ernest Rutherford

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

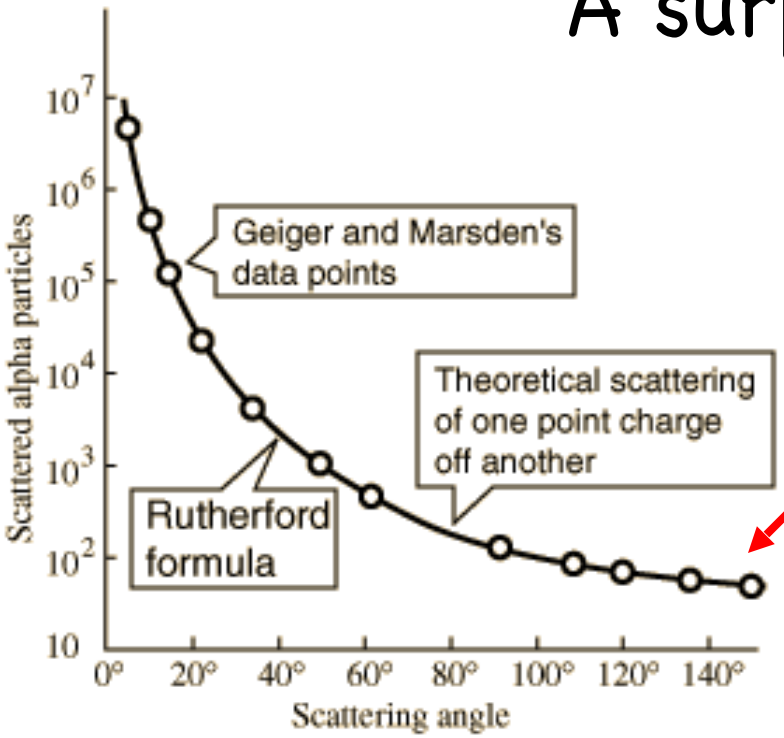
very light electrons should have no effect on the alpha's

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



Rutherford Scattering

A surprise

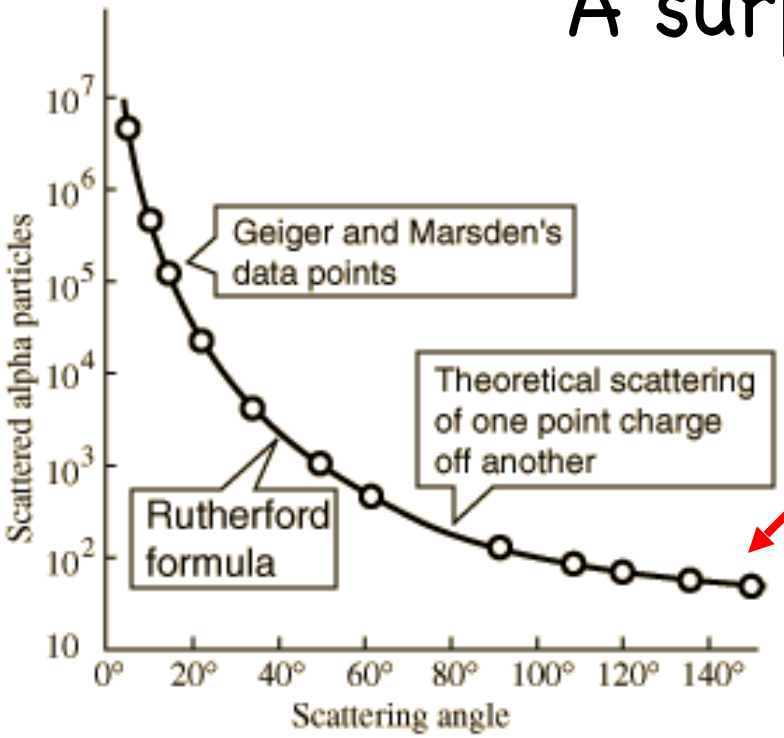


some of the alpha's scattered at large angles

Data is described by assuming alpha's scattered of a massive point charge

Rutherford Scattering

A surprise



some of the alpha's scattered at large angles

Data is described by assuming alpha's scattered of a massive point charge

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

The Nuclear Atom

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

How small is the nucleus?

Heisenberg Uncertainty Principle

Why we need large, expensive high energy accelerators

precision of measurement

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

momentum transferred

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

Rutherford couldn't resolve the nucleus. It looked like a point.

Discovery of the Neutron

1932

James Chadwick

Alpha particles interacting in air found to knock out neutral particles.

Rutherford had earlier discovered the proton (the nucleus of the hydrogen atom)

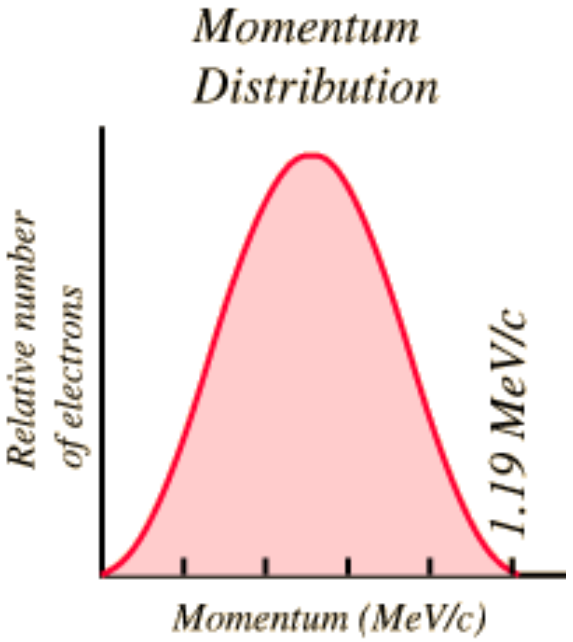
Atoms made out of:
protons, neutrons, electrons

The Neutrino

A free neutron decays
to a proton and electron
in about 15 minutes

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

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



Ghost-like neutrino

Predicted in 1930 by Pauli

Discovered in 1956 by Cowan and Reines

Pauli

Fundamental Particle Physics

1932

neutrino ν

electron e^-

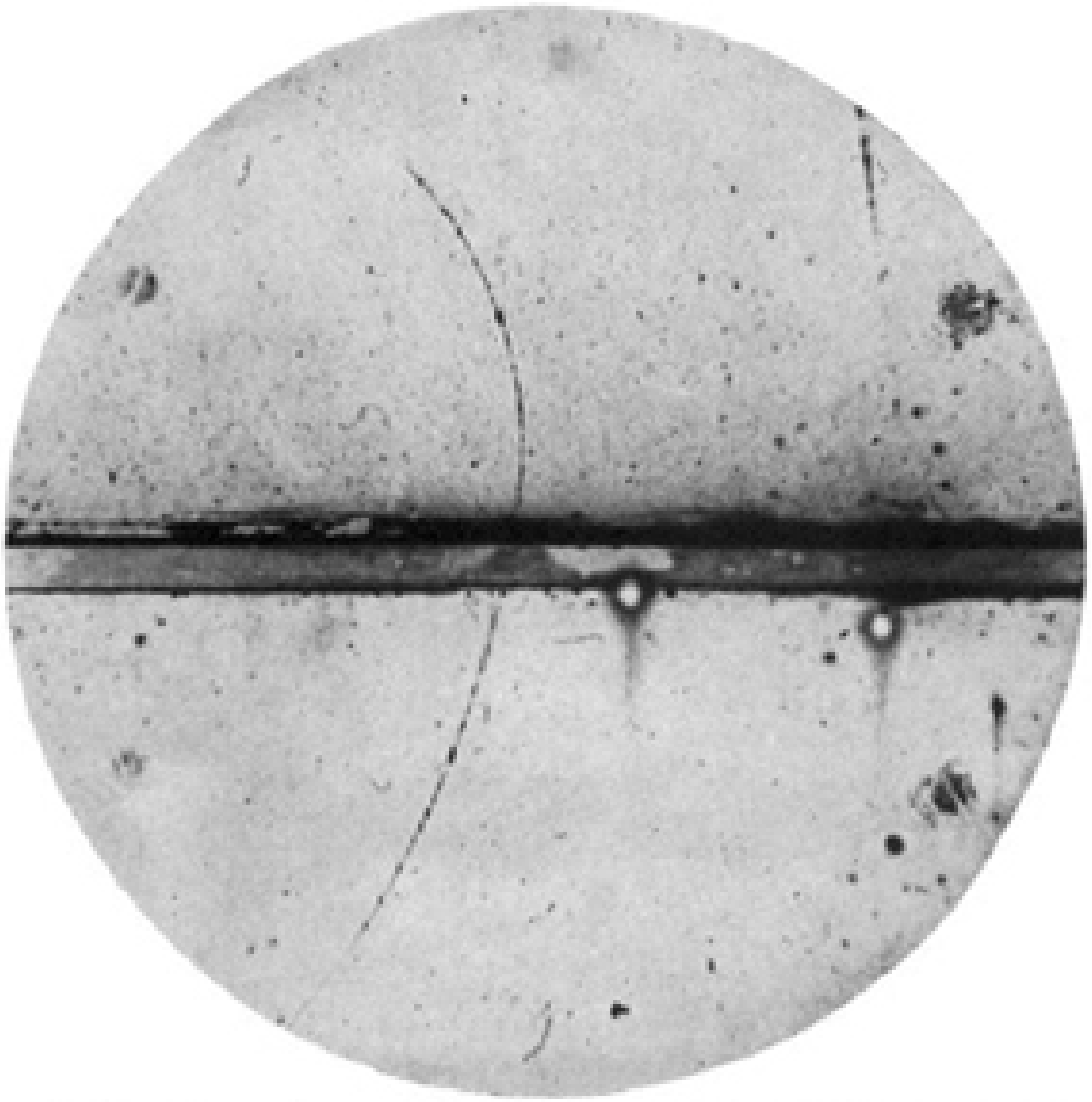
photon γ

proton p

neutron n

The Modern Period

1932 – 1974

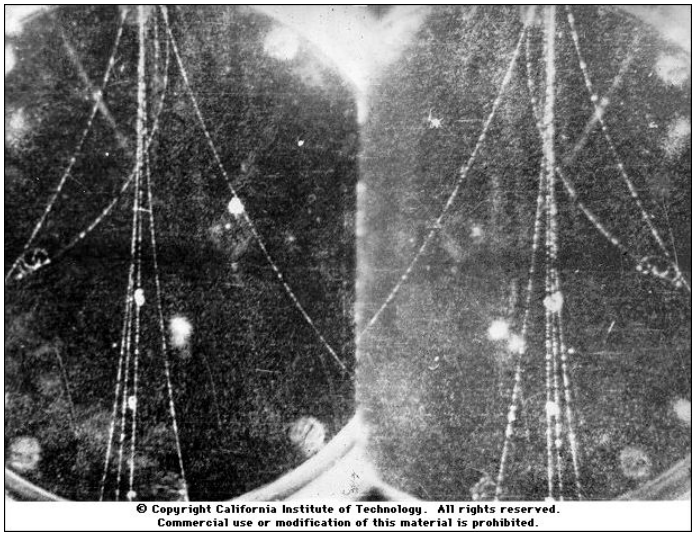


Cosmic Rays

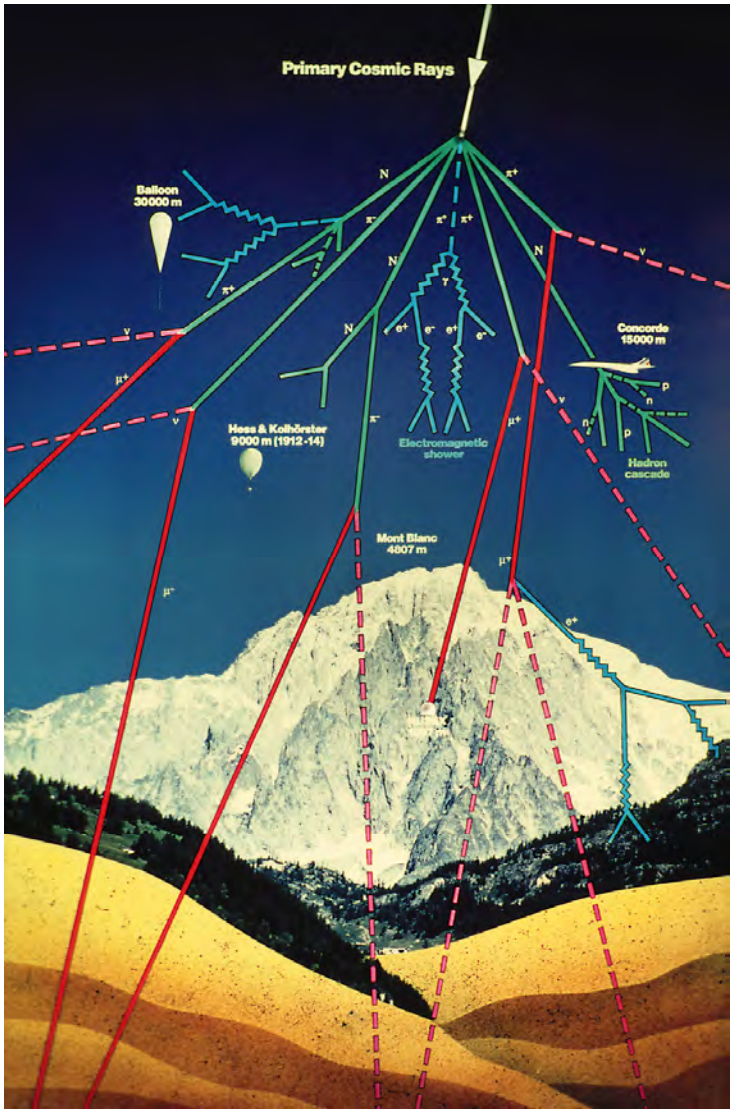
The cosmic accelerator

much higher energies
than available in the lab

with higher energies can
produce more massive particles

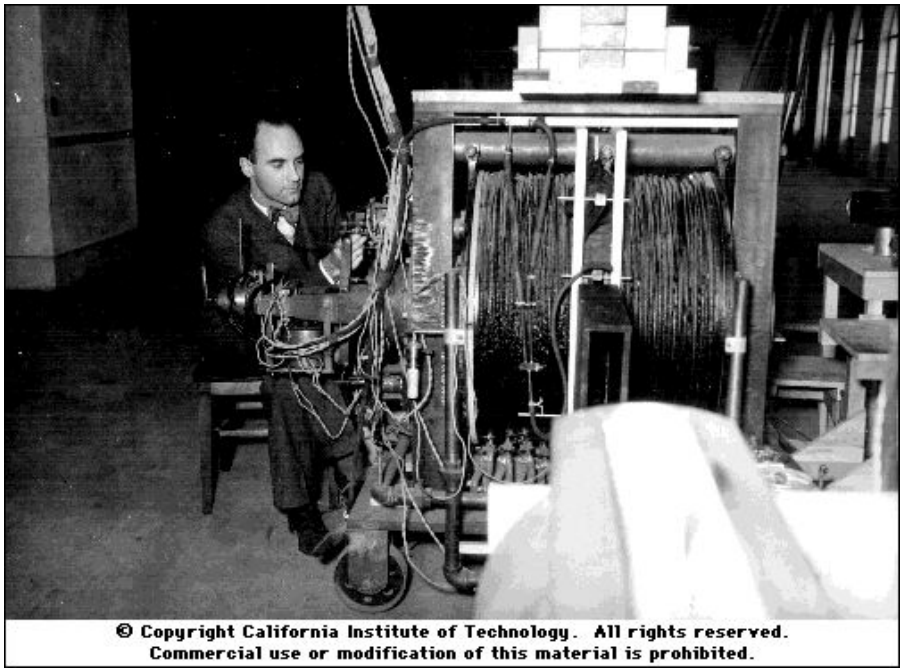


cloud chamber



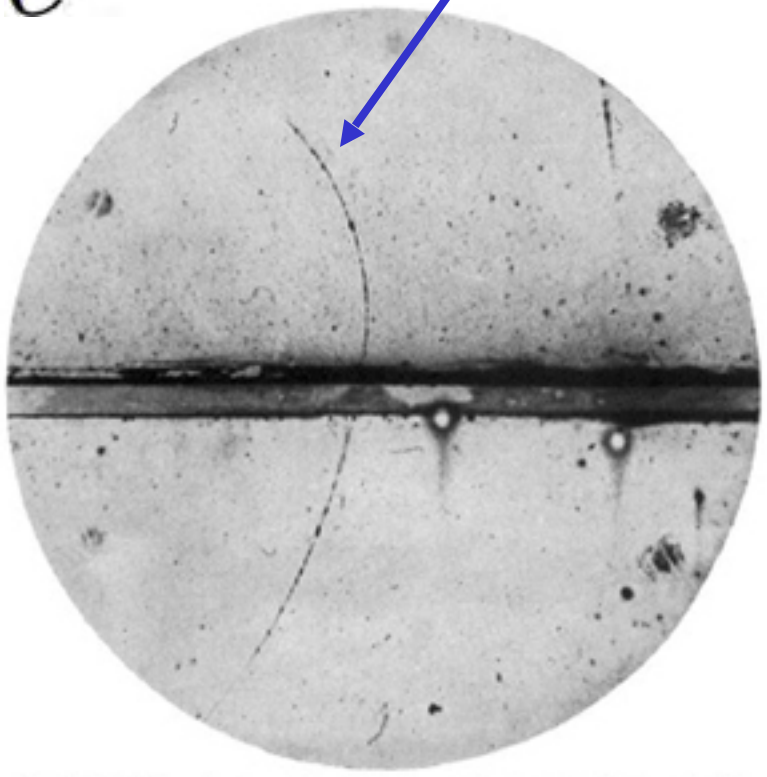
Antimatter

1932 Carl Anderson discovers anti-electrons (positrons)



positron track

e^+



Discovery of the Muon

1937: the muon a heavy electron discovered by Anderson

μ

Just like electron except about 200 times more mass

I.I. Rabi

Discovery of the Muon

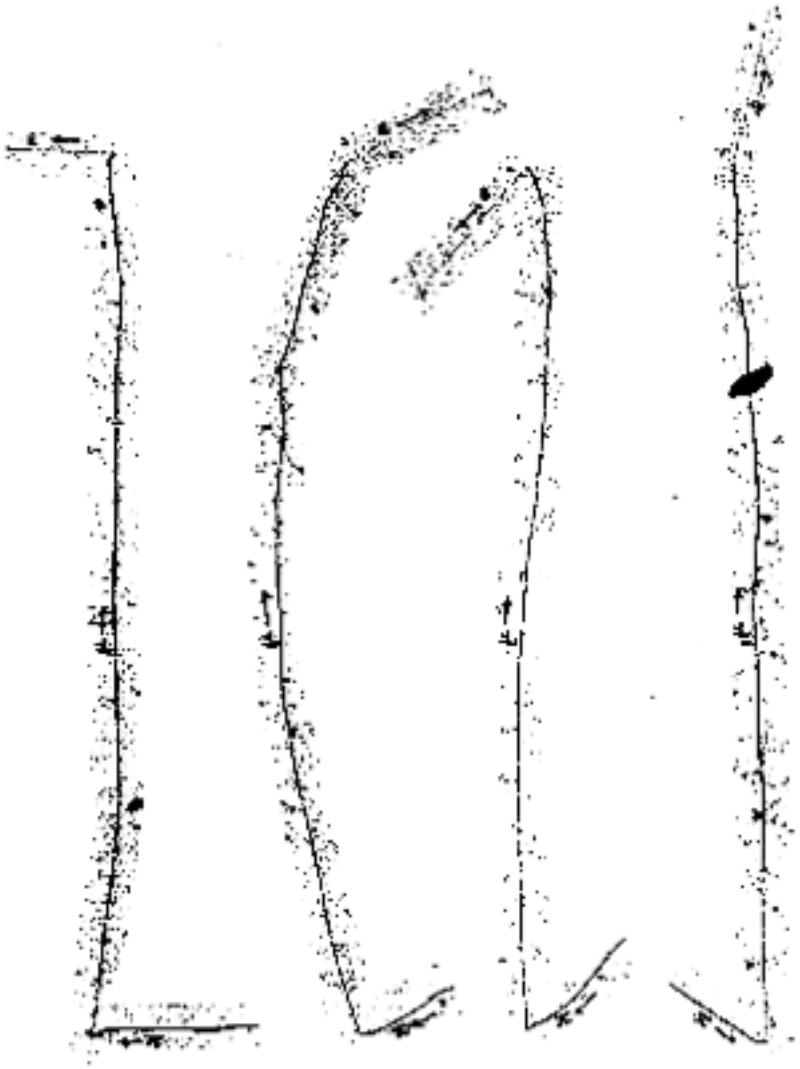
1937: the muon a heavy electron discovered by Anderson

μ

I.I. Rabi

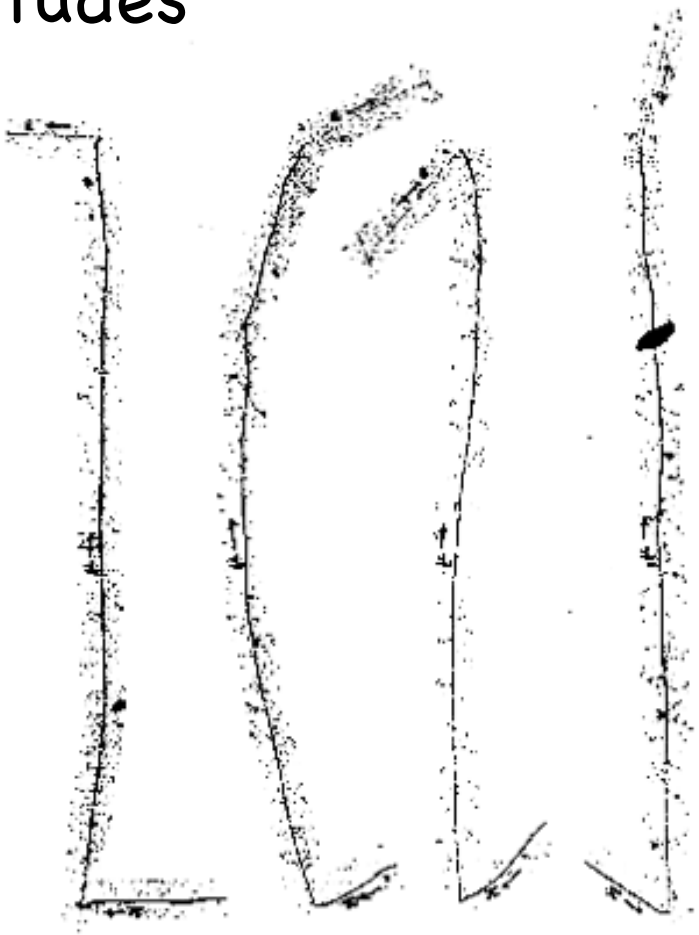
Just like electron except about 200 times more mass

Particle Discoveries



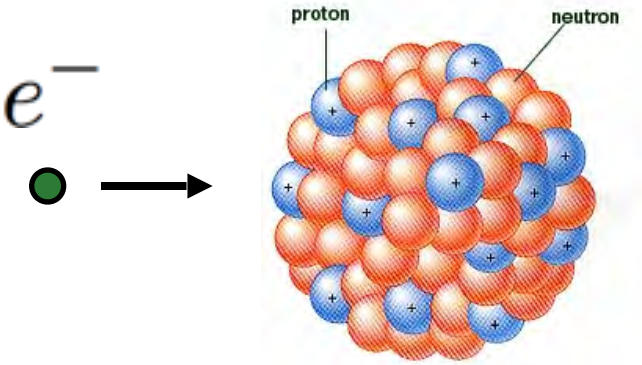
Particle Discoveries

1947: pions discovered using photographic emulsions at high altitudes

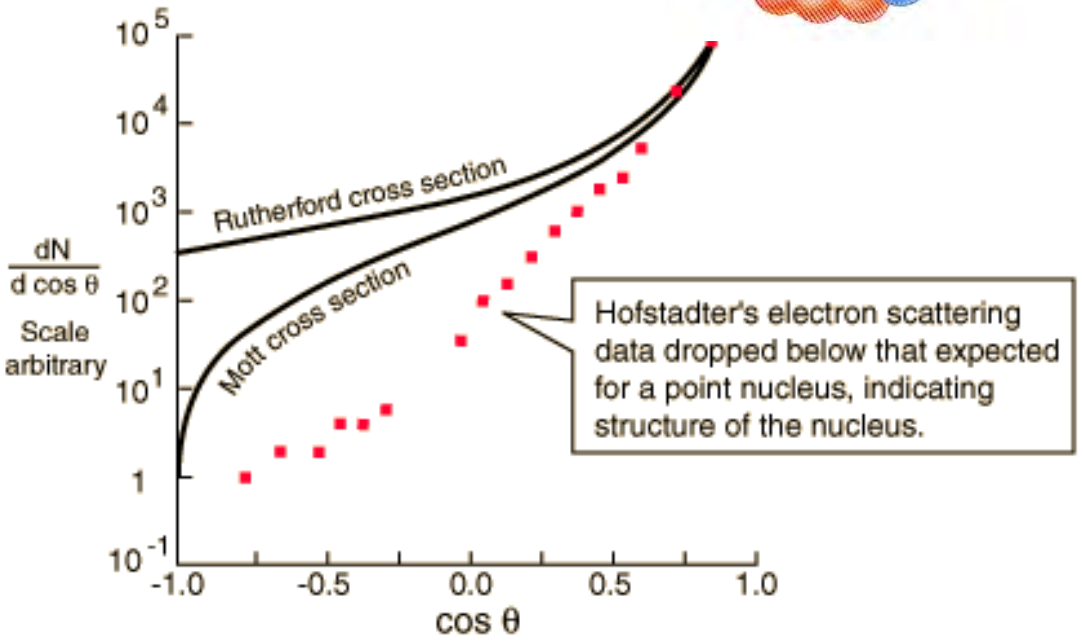


Structure of the Nucleus

1953 Scattered 125 MeV electrons off of nuclei



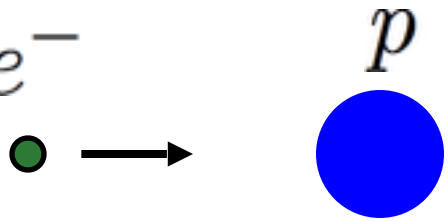
Hofstadter

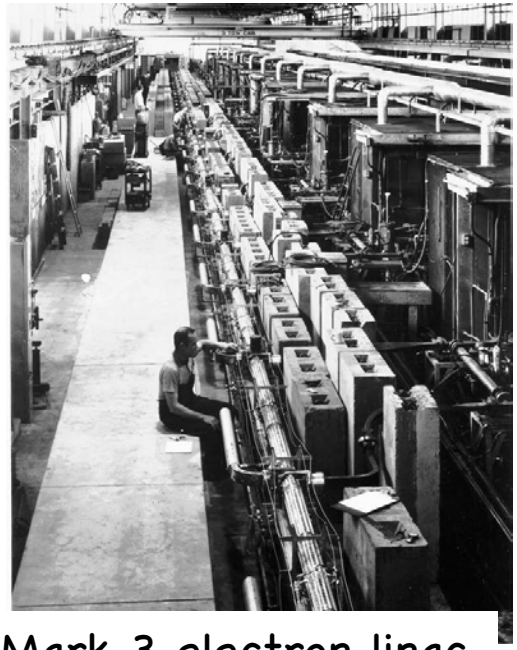


nuclear size: $\sim 10^{-13}$ cm

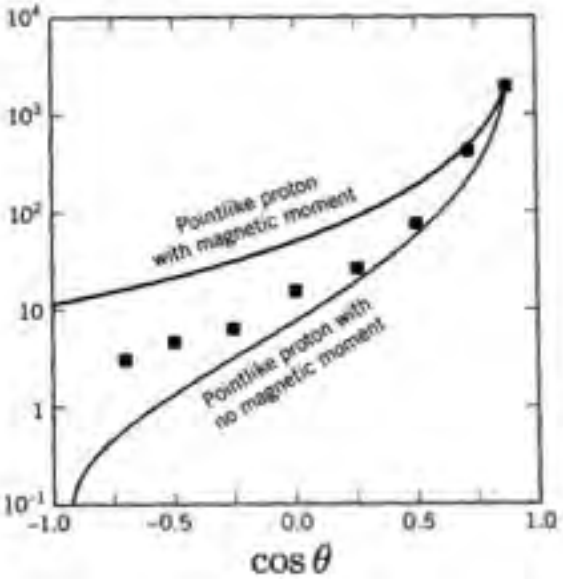
Structure of the Proton

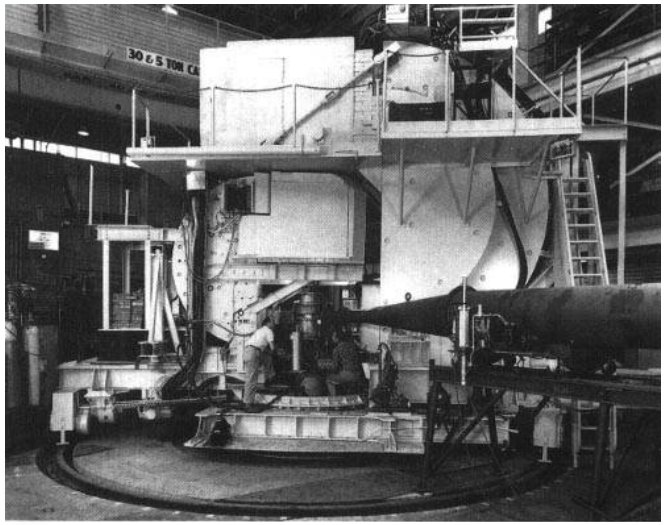
1956 Scattered 550 MeV electrons off of nuclei





Mark 3 electron linac at Stanford University



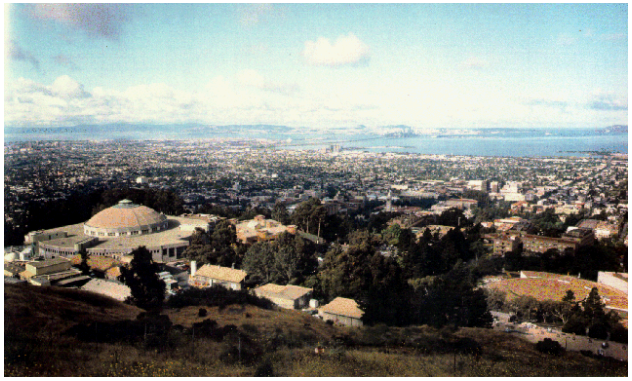


Hofstadter's spectrometer

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

The Bevatron

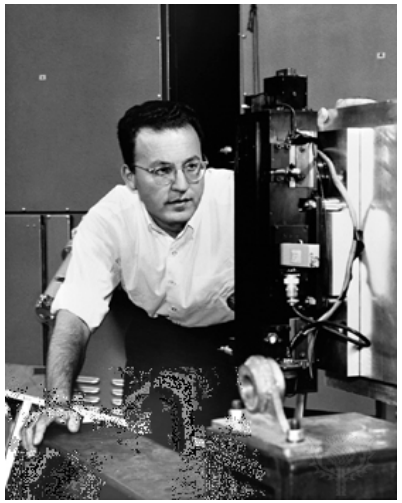
6 GeV proton synchrotron
in the hills of Berkeley



Designed to discover
the anti-proton

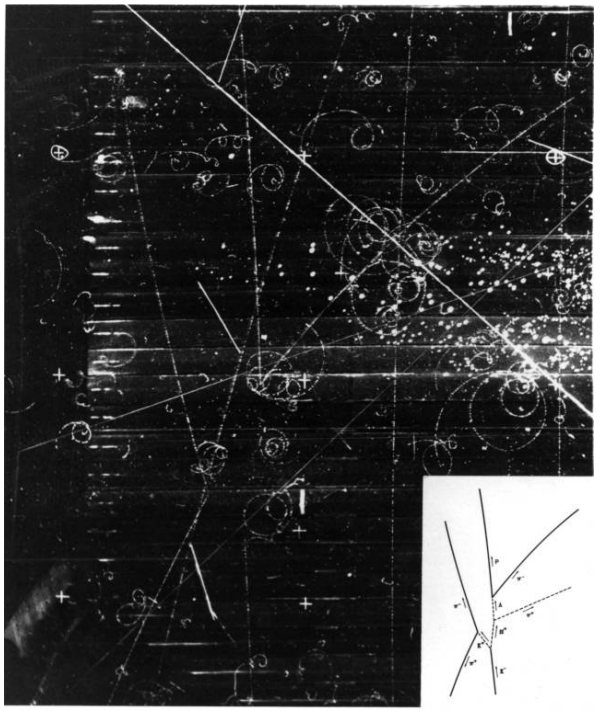
"Seeing" Particles

The bubble chamber



Donald Glaser

Luis Alvarez



The Particle Zoo

Hundreds of new particles discovered 1955 - 1965.

What does it all mean?

Quarks

1964

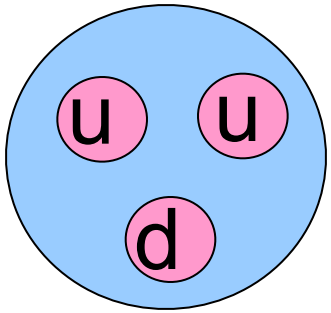
Murray Gell-Mann

Three quarks

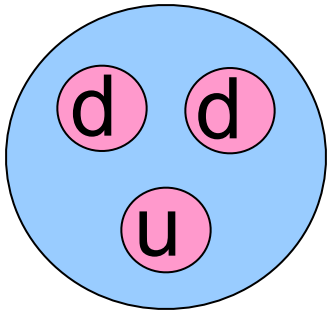
up down strange

mesons: $q\bar{q}$

baryons: qqq

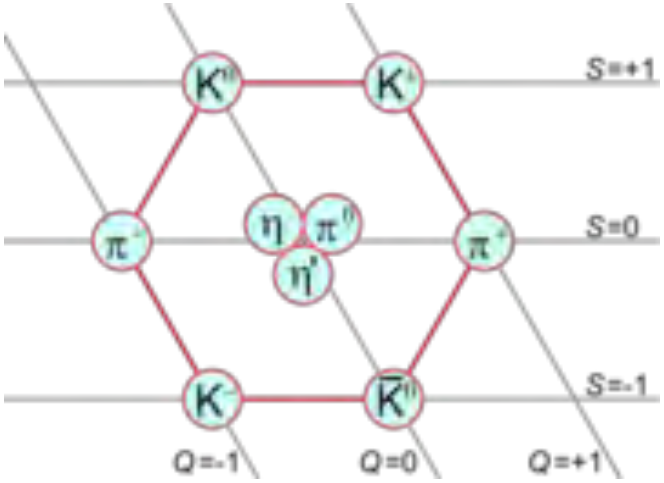


proton

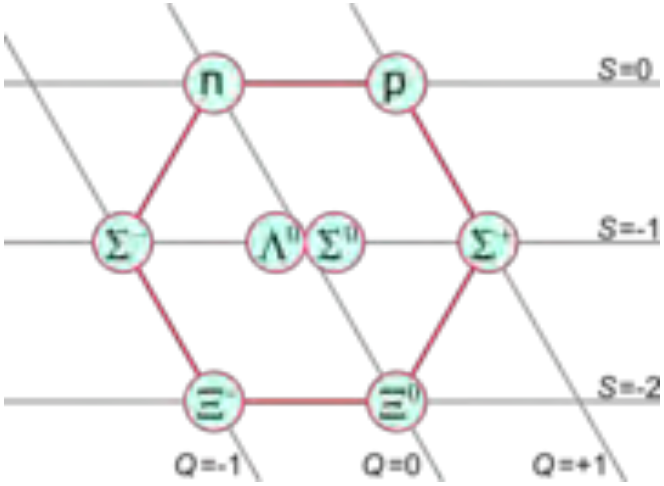


neutron

Classification Again



meson octet

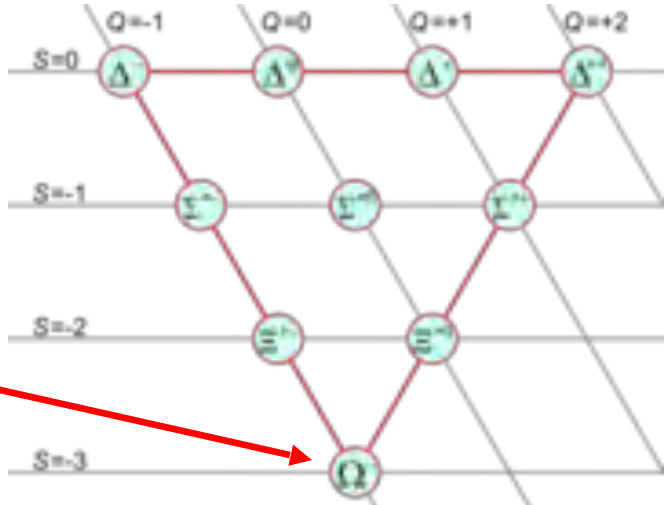


baryon octet

prediction:

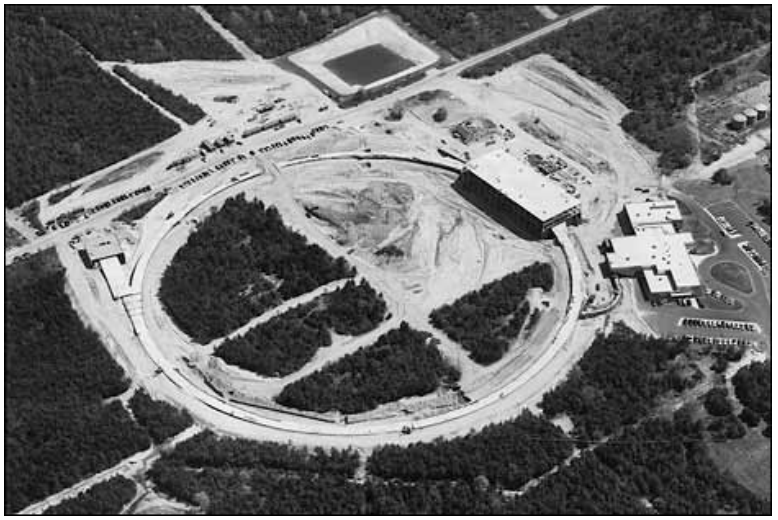
Ω^-

bound state of
3 strange quarks



baryon decaplet

Brookhaven



The AGS

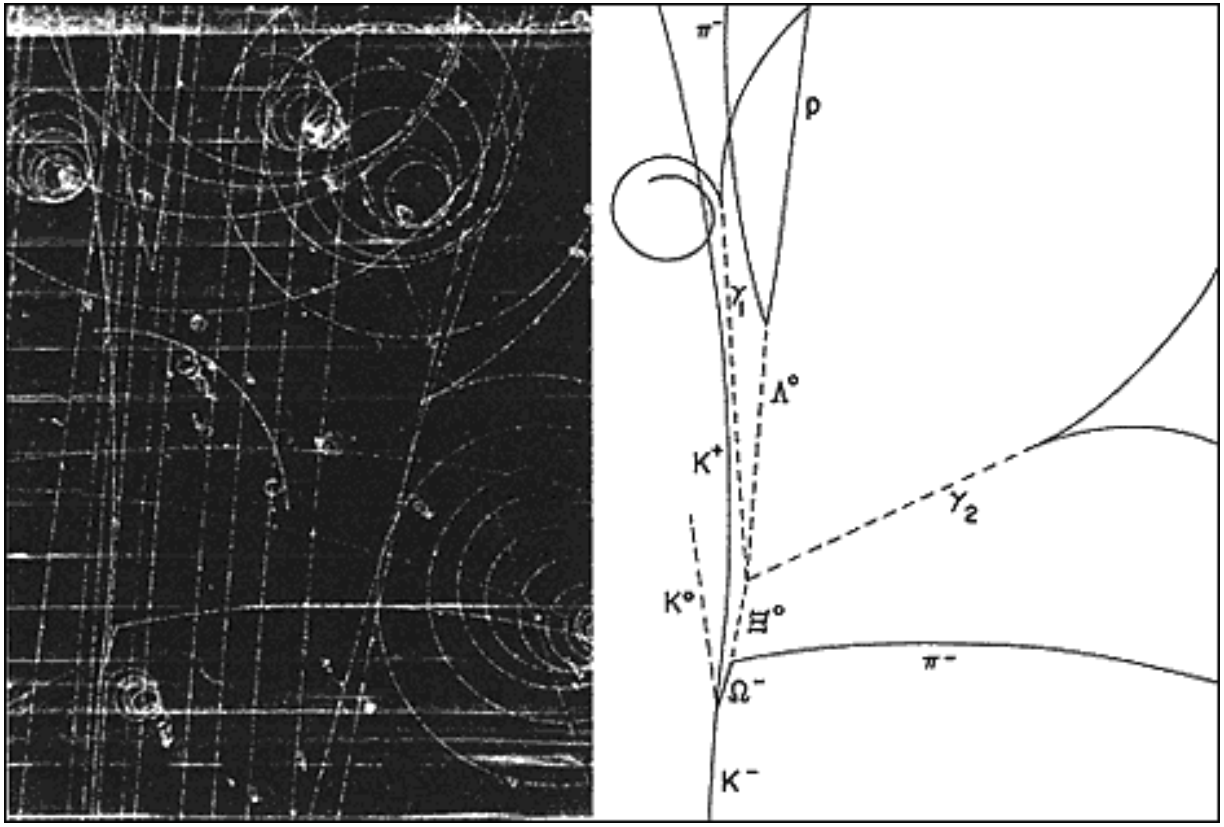
33 GeV proton synchrotron

Discovery of the Omega Minus

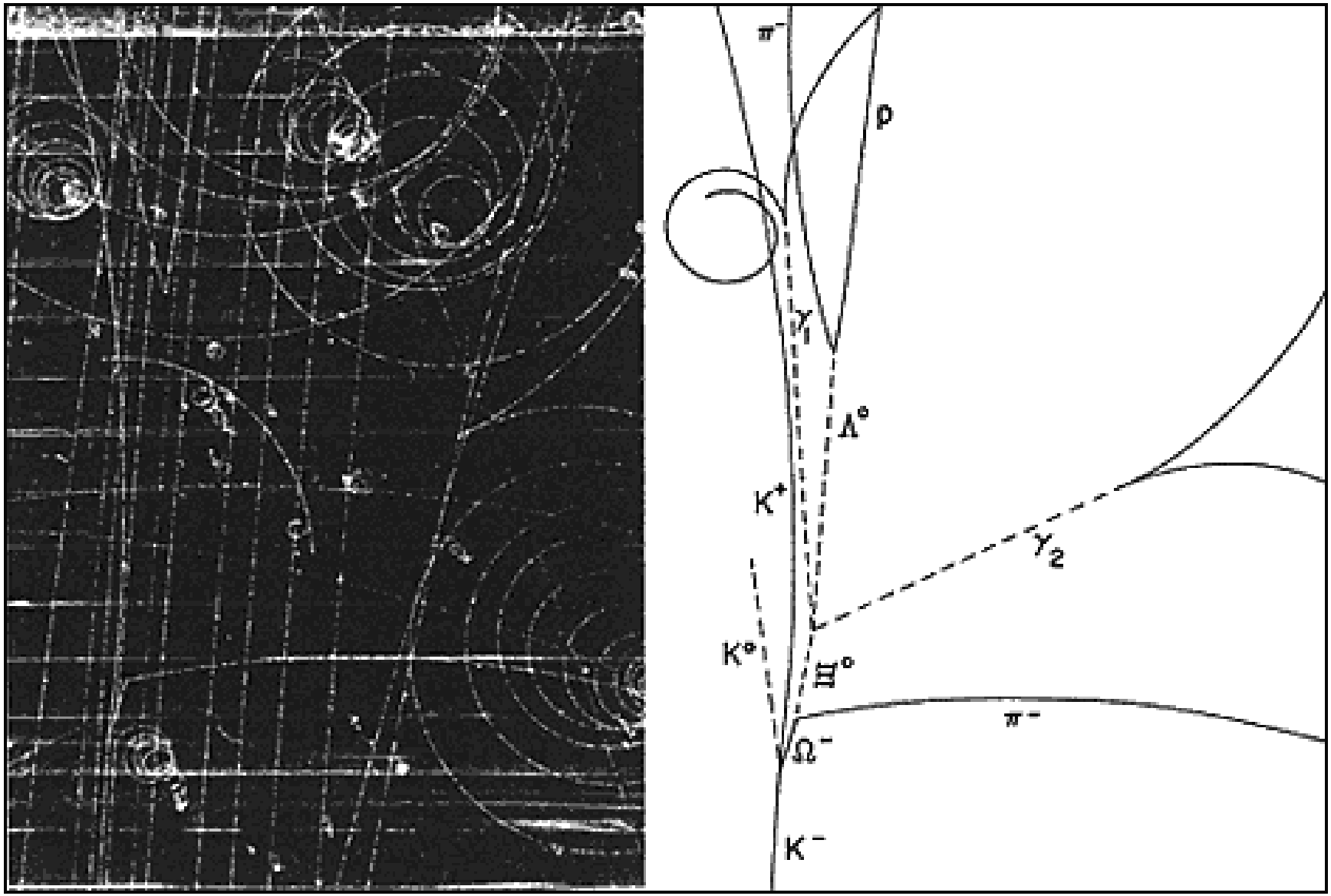
1964

Nick Samios

80 - inch bubble chamber



Discovery of the Omega Minus



Stanford Linear Accelerator Center

SLAC

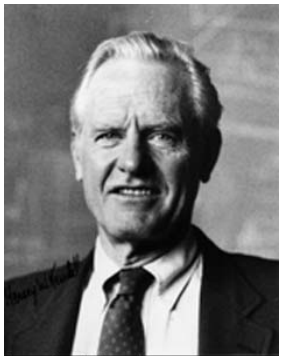
30 GeV electrons

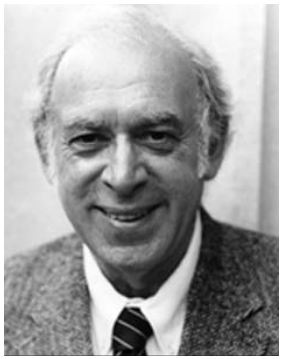
2-mile long linear accelerator

Inside the Proton

1968

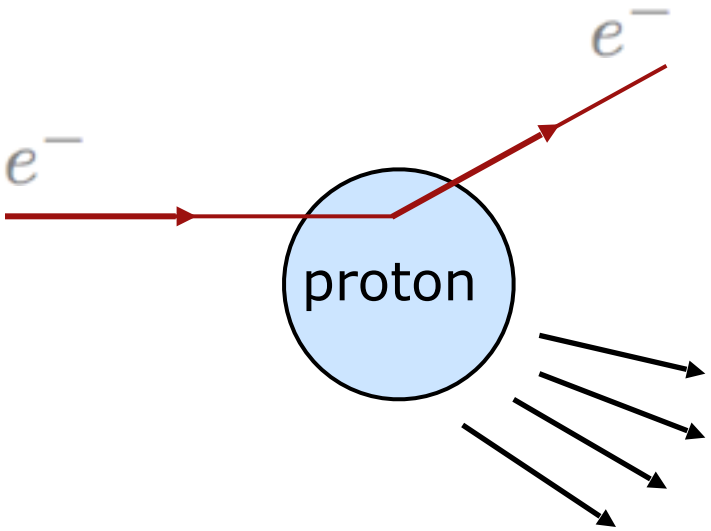
SLAC - MIT Group


Kendall


Friedman


Taylor

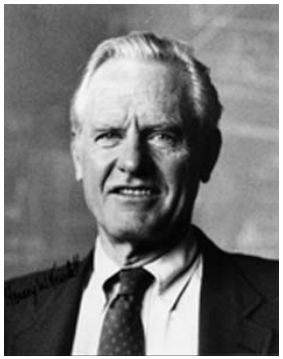
deep inelastic scattering

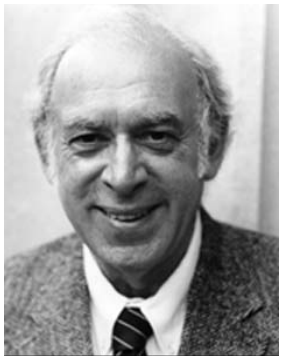


Inside the Proton

1968

SLAC - MIT Group

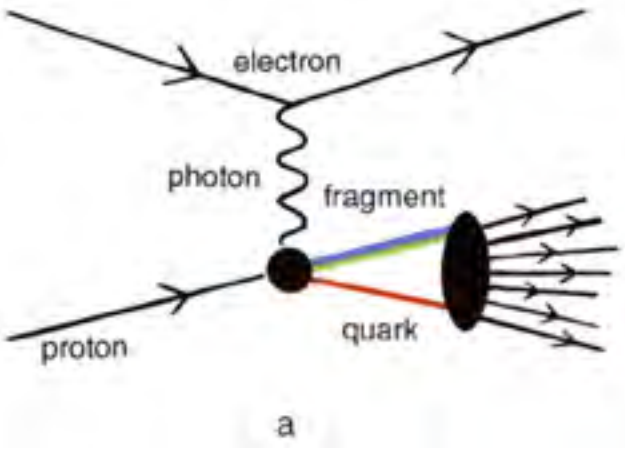

Kendall

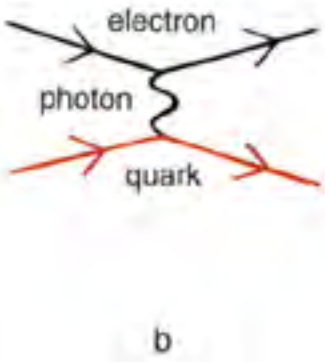

Friedman


Taylor

deep inelastic scattering

Rutherford scattering off of point objects again





Fundamental Particle Physics

1974

leptons

ν_e ν_μ

e^- μ^-

quarks

u

d s

gauge boson

γ

The Golden Period

1974 –1982

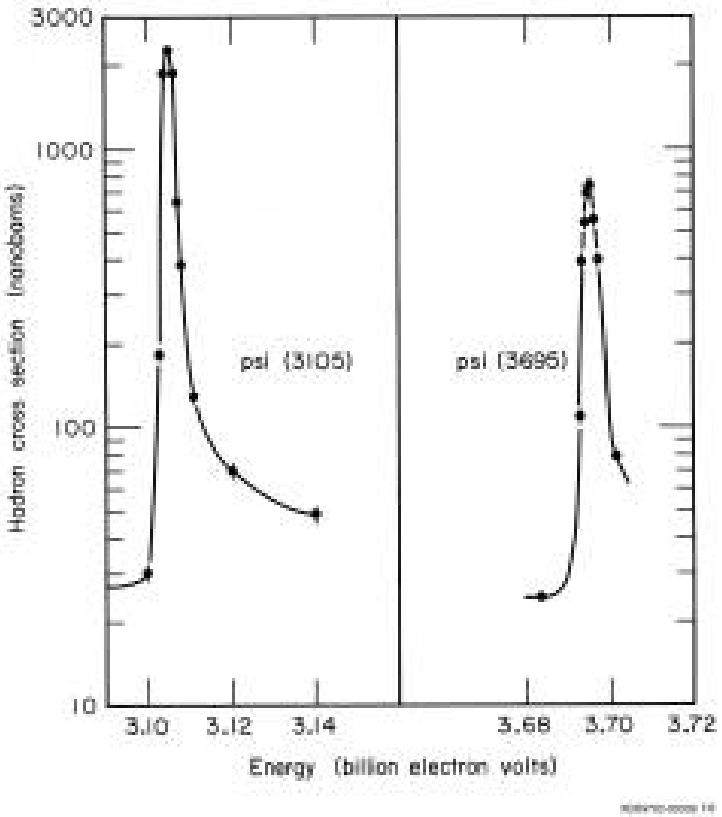
Discovery of a New Quark

Burt Richter

1974

resonance

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



SPEAR

Electron-positron collider

J/ψ

bound state of charm and anti-charm quarks

Charmonium

Simultaneous Discovery

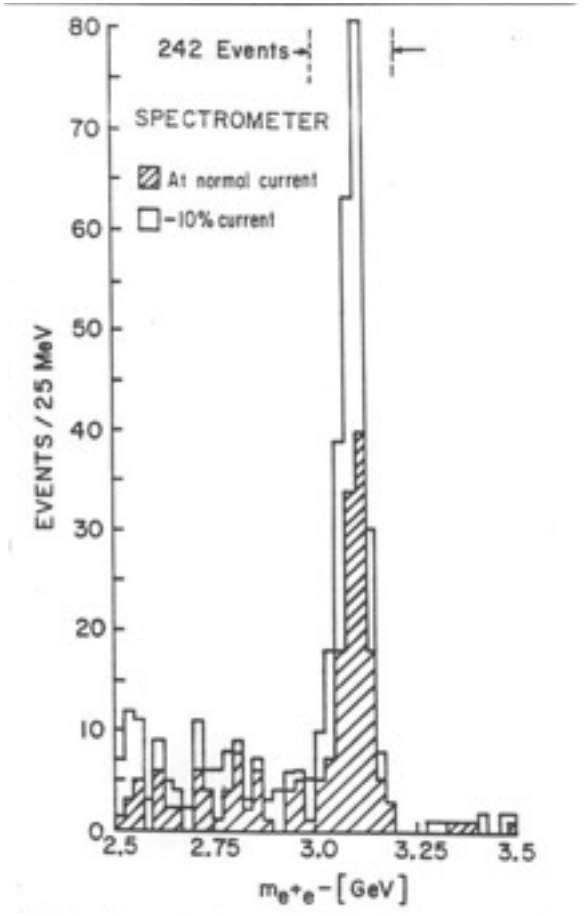
Sam Ting

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

$$J/\psi \rightarrow e^+\,e^-$$

Double-arm spectrometer

AGS Experiment



Discovery of a New Heavy Electron

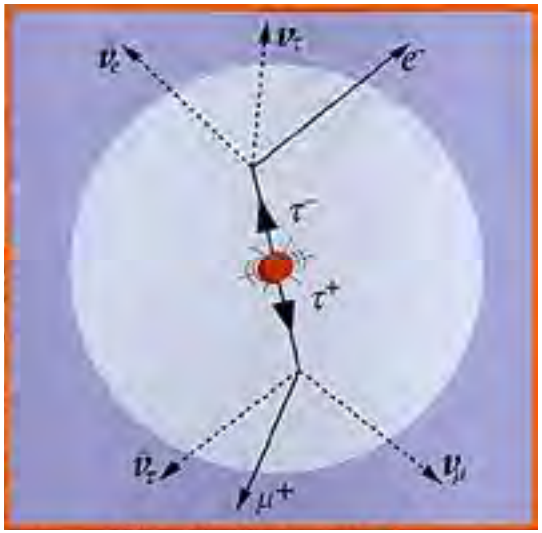
1975 The tau lepton

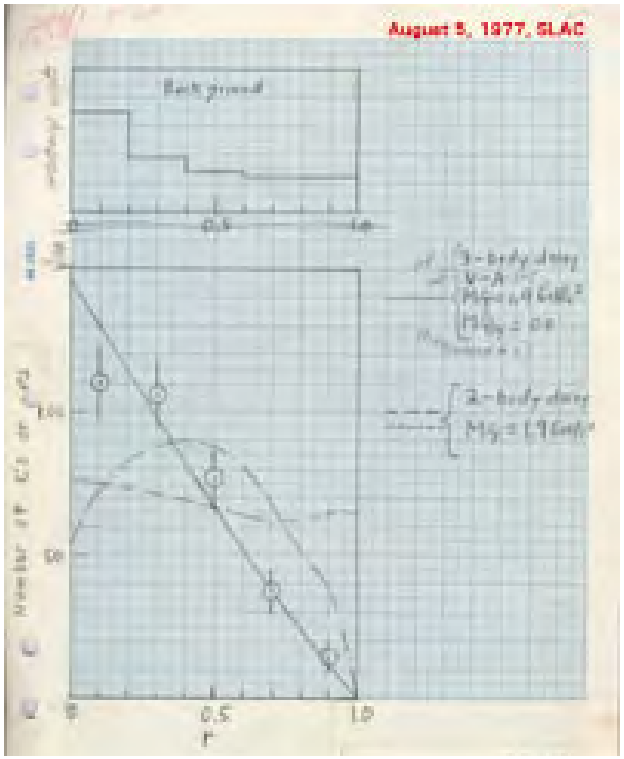
Marty Perl

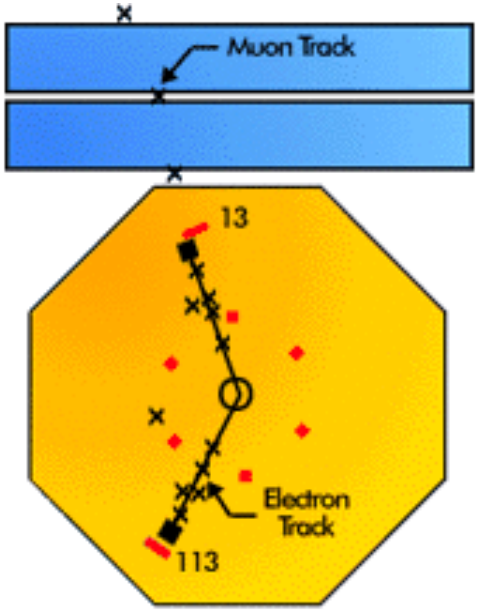
$$e^+ e^- \rightarrow \tau^+ \tau^-$$

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

Just like electron except about 2000 times more mass







Fermilab

400 GeV Proton Synchrotron

2 km diameter ring

Robert Wilson

Discovery of Another New Quark

Leon Lederman

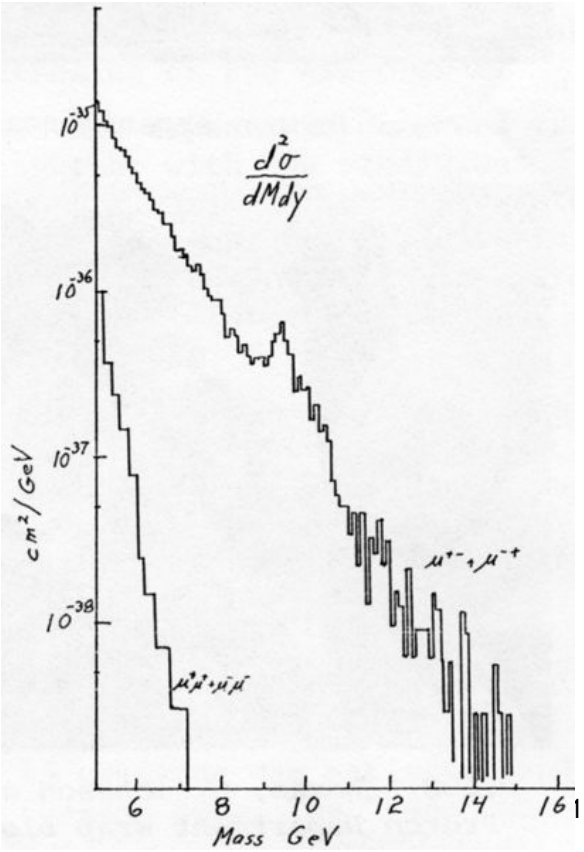
1976

Υ

bound state of bottom and anti-bottom quarks

$$p\,p \rightarrow \Upsilon + X$$

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



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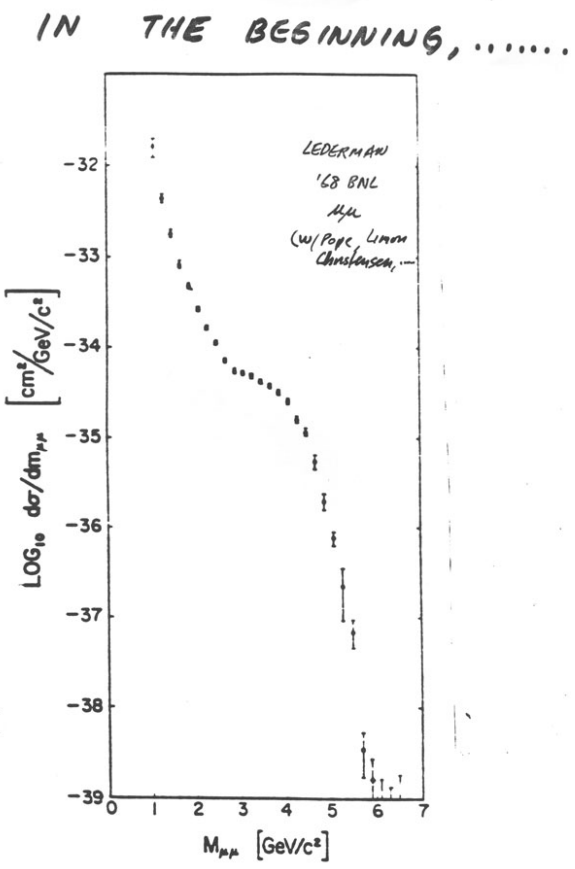
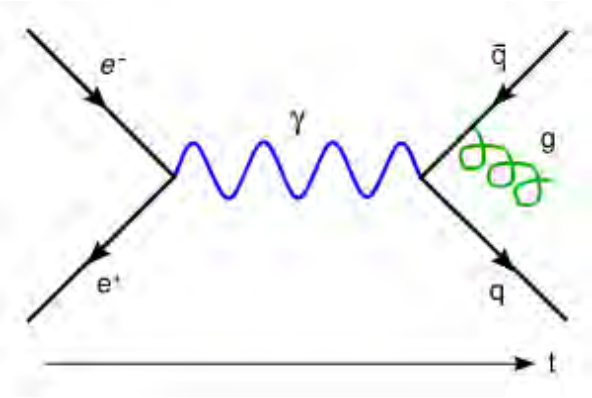


Discovery of the Gluon

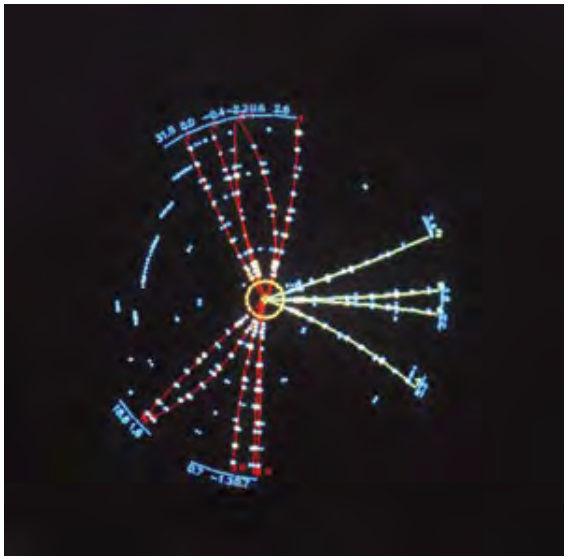
1979

Sau Lan Wu



30 GeV e^+e^- Collider

PETRA



carrier of the strong force
Quantum Chromo Dynamics

binds quarks together
to make proton

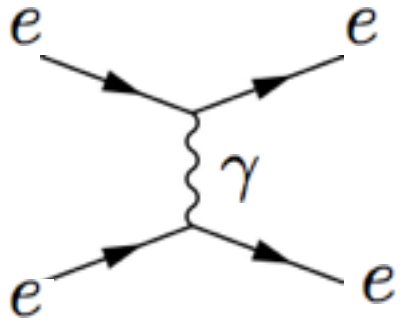
The Standard Model

Quantum Electrodynamics

charged particles interacting

by photon exchange

atomic physics

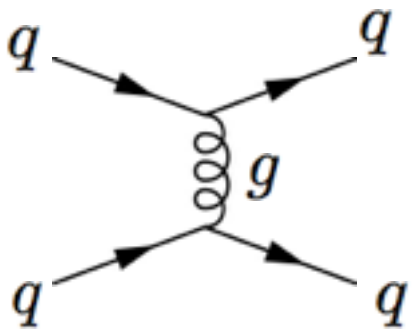


Quantum Chromodynamics

quarks interacting

by gluon exchange

binding of quarks



Weak Force

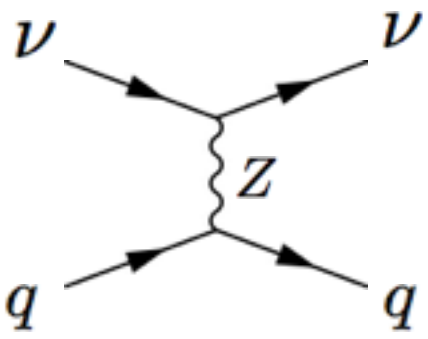
particles interacting

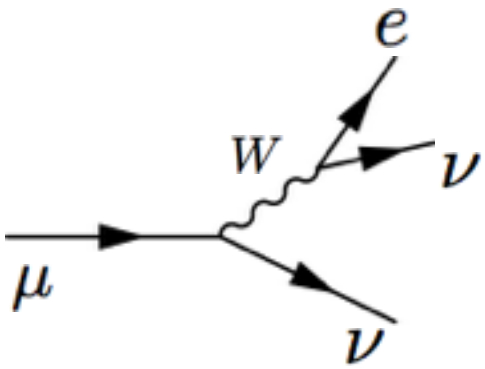
by W and Z exchange

heavy lepton decay

heavy quark decay

neutrino interactions





CERN

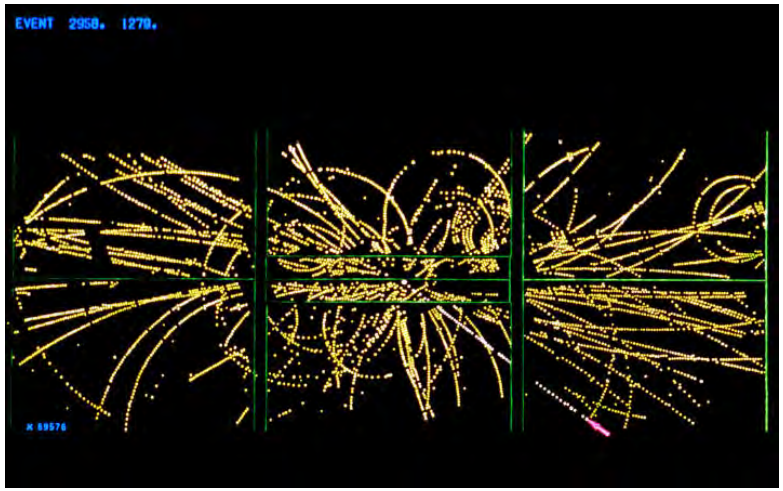
Off to the French Alps

proton – antiproton
collisions at 450 GeV

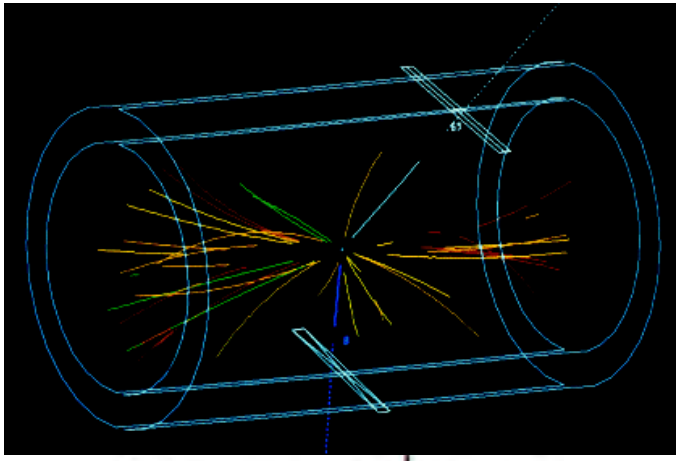
Discovery of the W and Z

1982

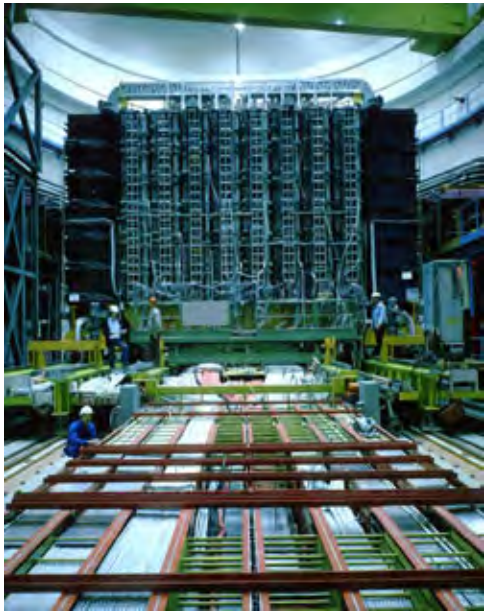
Rubbia



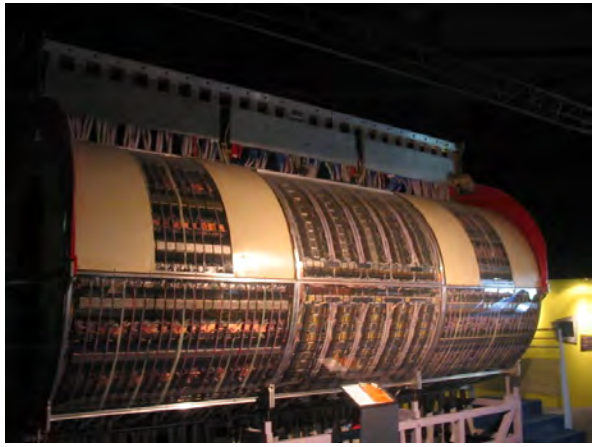
$W \rightarrow e\nu$

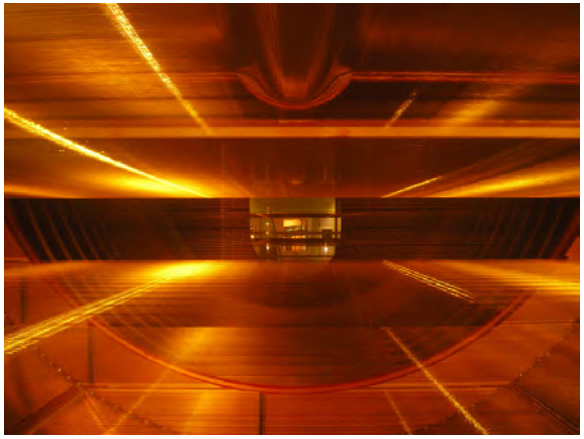


$Z \rightarrow e^+e^-$



UA 1 Detector





Fundamental Particle Physics

1982

leptons

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

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

quarks

$$u \quad c$$

$$d \quad s \quad b$$

gauge bosons

$$\gamma$$

$$g$$

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

The Recent Period

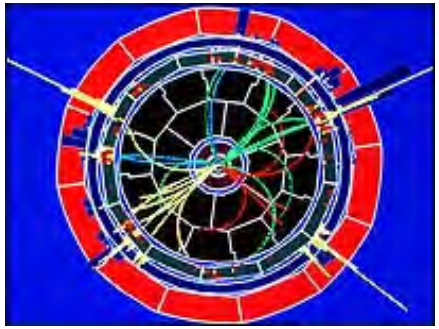
1982 – 2008

LEP

1989 - 2000

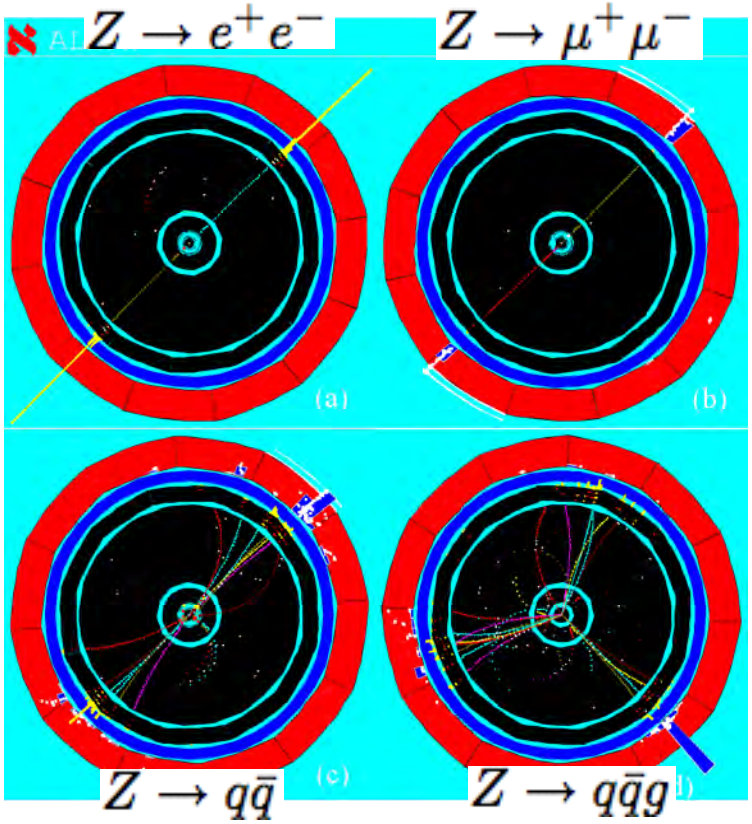
100 GeV electron - positron collisions at CERN

27 kilometer tunnel

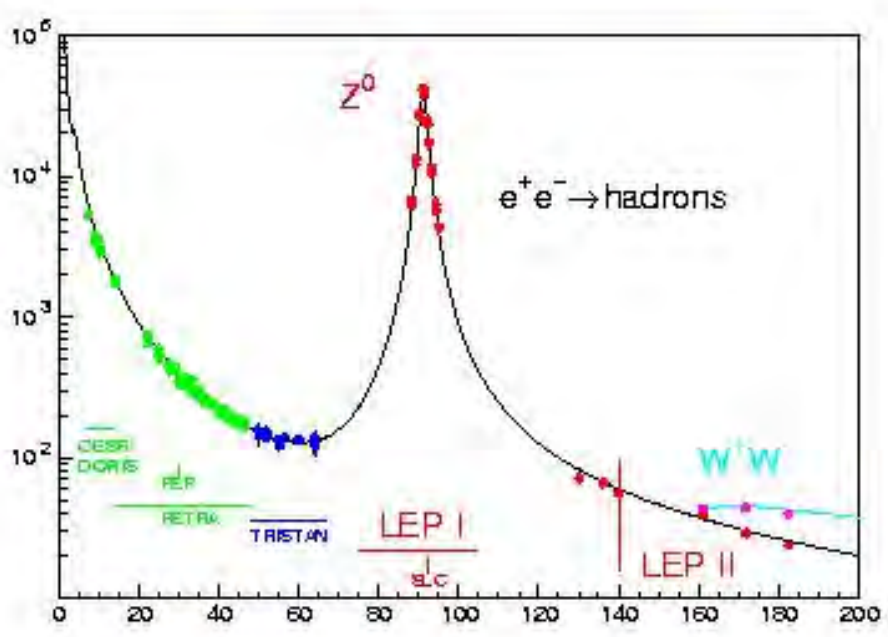


Z Factory

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



Aleph Detector



Precision Tests of Standard Model

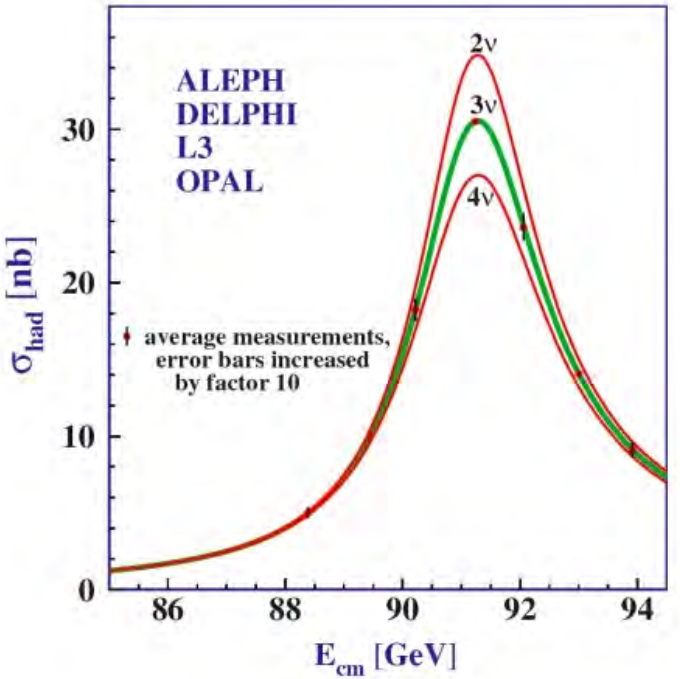
- Standard Model tested to 0.1% level
  in agreement with all measurements
  down to 10^{-16} cm

- Only three light neutrinos $Z \rightarrow \nu\bar{\nu}$

- Higgs still missing

$$e^+e^- \rightarrow ZH$$

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



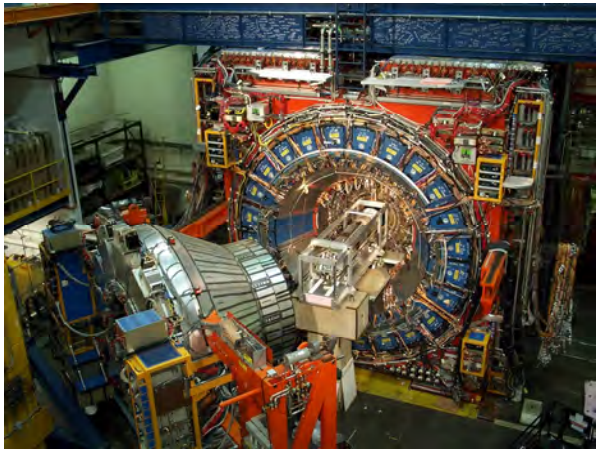
Discovery of the Top Quark

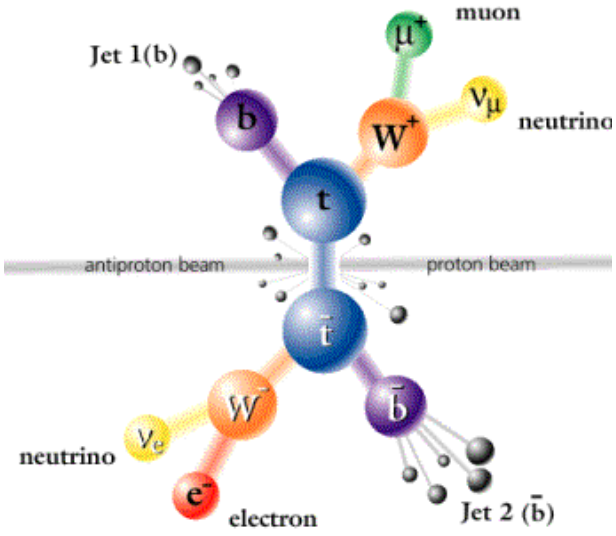
1995 2 TeV Proton - Antiproton collisions

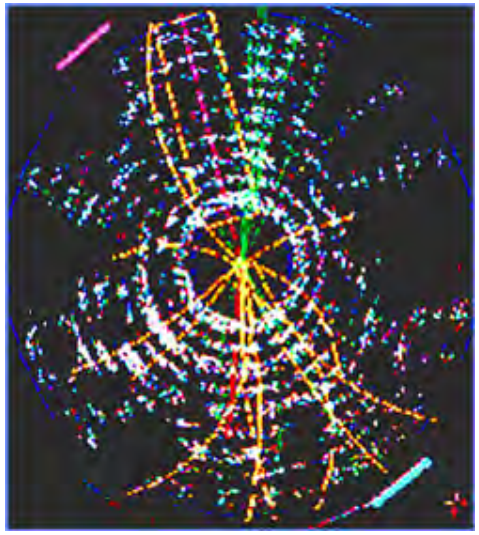
DO Collaboration

Fermilab Tevatron Collider

Production top anti-top







Fundamental Particle Physics

2008

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

$$\gamma$$

$$g$$

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

Higgs

missing

SM Summary

Complete, consistent theory of fundamental physics

- Fundamental constituents:

  6 quarks and 6 leptons
  plus antiparticles

- Three fundamental forces:

Electromagnetic	Strong	Weak
mediated by photons	mediated by gluons	mediated by W^+ W^- Z^0

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

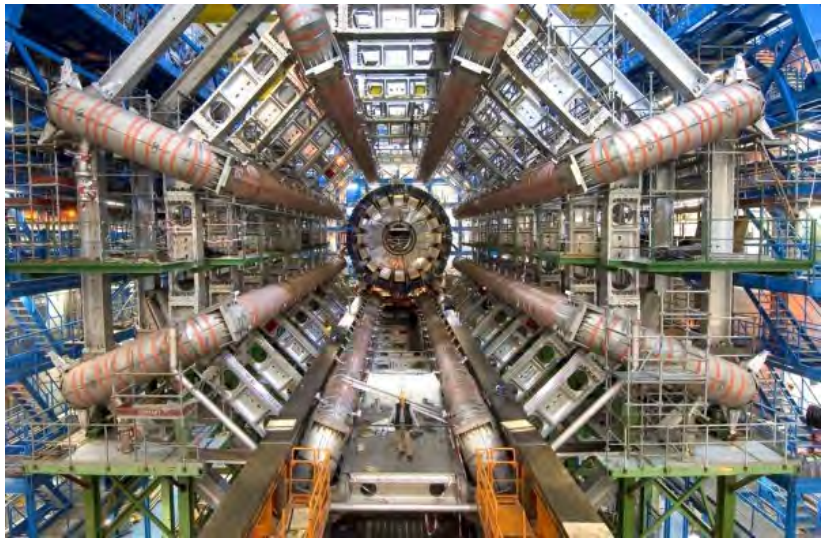
- Needs Higgs particle to be complete

The Large Hadron Collider

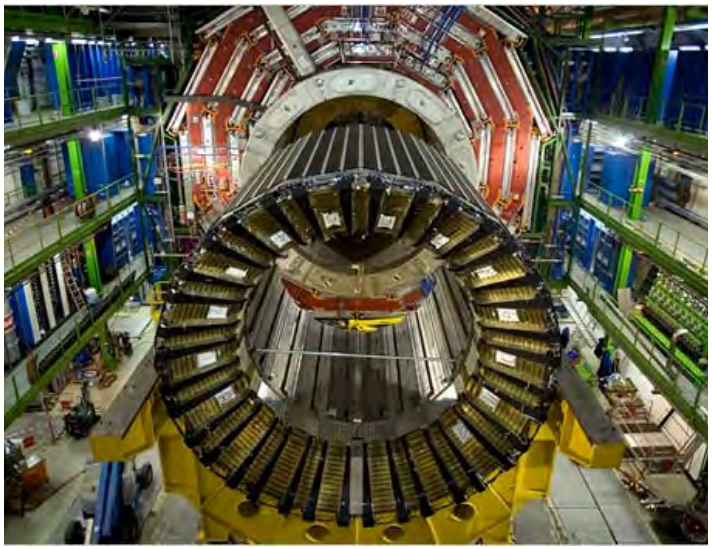
2008

14 TeV proton antiproton collisions in the LEP tunnel

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



Atlas Detector



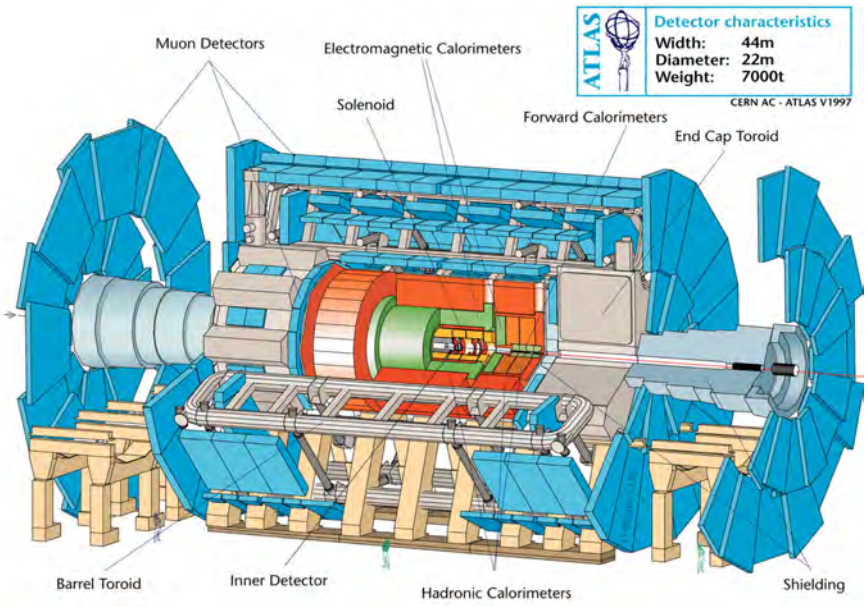
CMS Detector

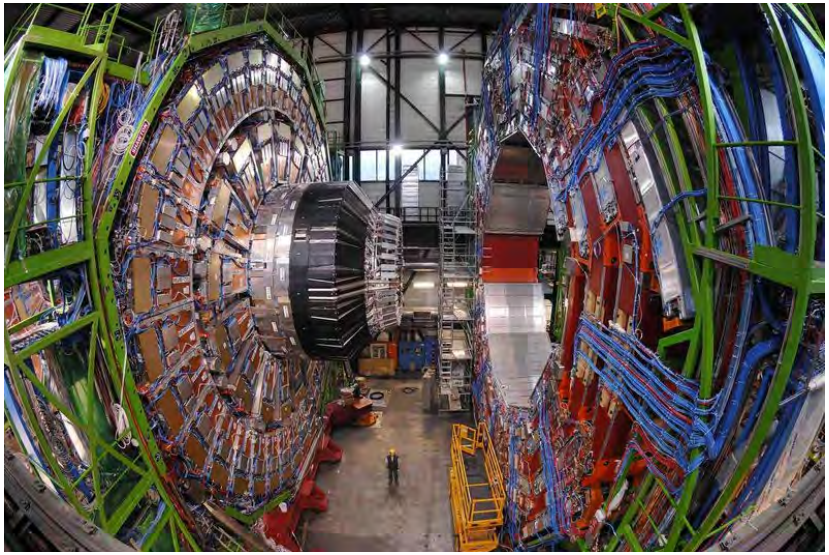
The Current Period

2009 – 2015

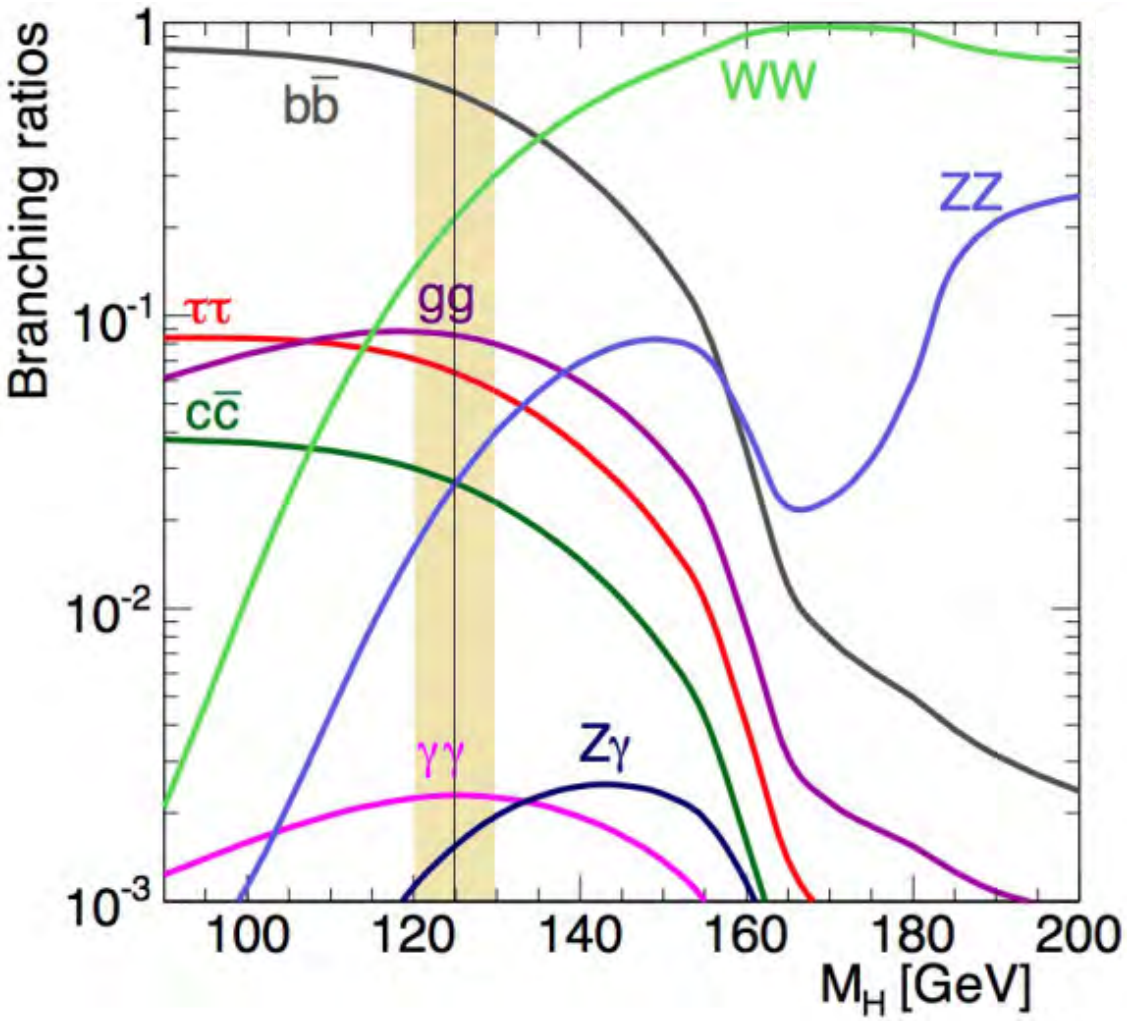
The Large Hadron Collider

Big Detectors, Big Collaborations





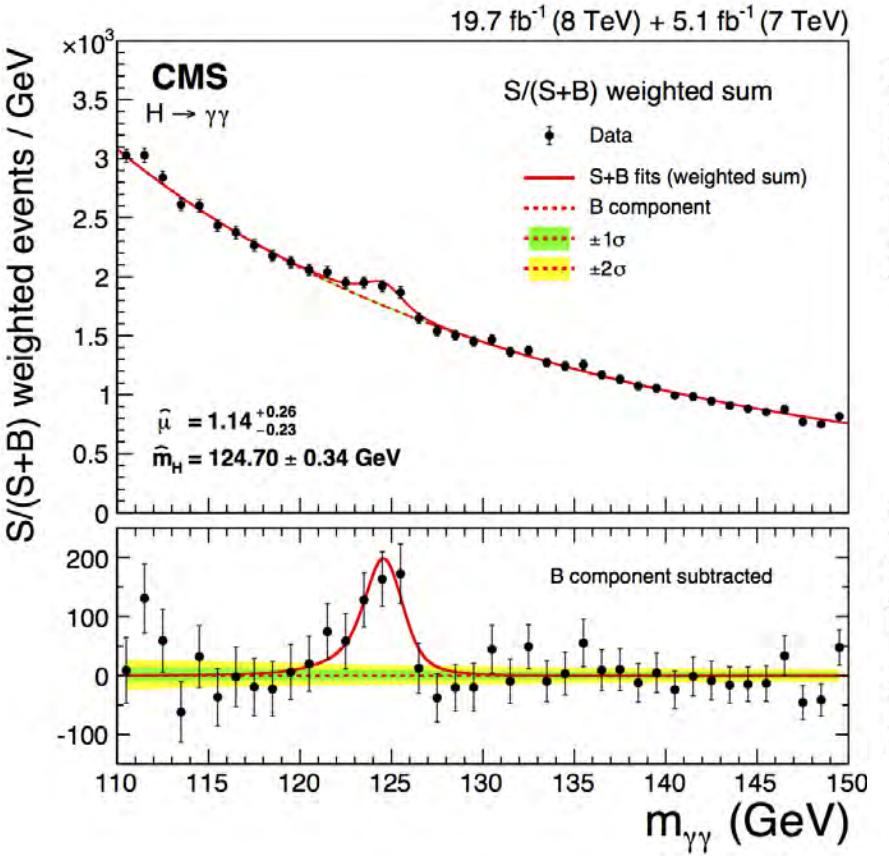
Higgs Decay Fractions



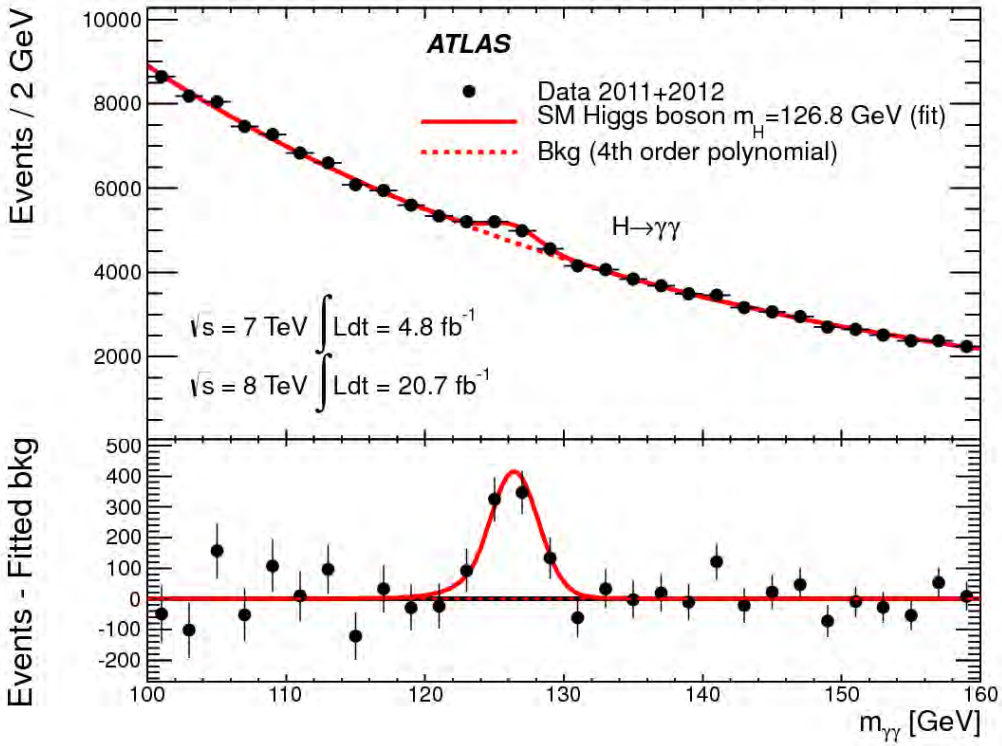
$H \to b\bar{b}$	58%
$H \to W^+W^-$	22%
$H \to gg$	8.6%
$H \to \tau^+\tau^-$	6.3%
$H \to c\bar{c}$	2.9%
$H \to ZZ$	2.6%
$H \to \gamma\gamma$	0.2%

The Higgs Discovery

CMS



ATLAS



Problems with the Standard Model

- "Natural" mass of the Higgs is 10^{19} GeV/c^2.
  Why is it 17 orders of magnitude smaller?
- The Standard Model does not include gravity.
- Why does matter dominate over antimatter?
- Why are there three generations of matter particles?
- What explains the values of the masses?
- Too many parameters (27).
- Higgs mechanism seems ad hoc.
- Doesn't account for Dark Matter
- Doesn't account for Dark Energy

LHC Physics

Discovery of the Higgs Boson

- Missing ingredient of the Standard Model (SM)
- Now have complete mathematically consistent theory
- Agrees with all experiments down to 10^{-18} m scale

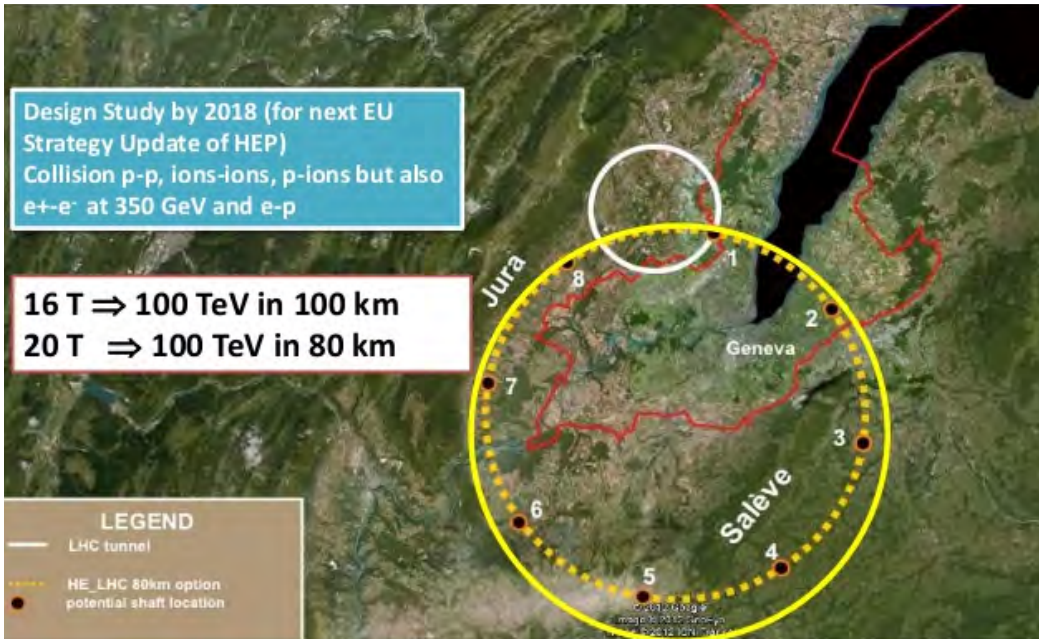
What lies beyond the SM at smaller distance (higher energy) scales?

- Measure decay fractions of Higgs to 1% precision
- Search for Supersymmetry (SUSY)
  - Might explain why Higgs is unnaturally light
  - Lightest SUSY particle provides Dark Matter candidate
- Search for other exotics
  - Vector - Like quarks, . . .
- Find the unexpected

Future Circular Collider

A 100 TeV collider under discussion at CERN / China

No guarantee of new physics



Design report in 2018

Turn on in the 2050?