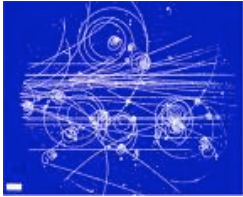
The background of the slide is a complex, black-and-white image showing particle tracks and detector patterns. It features numerous overlapping lines, some straight and some curved, with various symbols like 'X' and dots scattered throughout. The overall appearance is that of a technical drawing or a photograph of a particle detector's output, possibly a bubble chamber or a similar tracking device. The tracks are dense and crisscross the entire frame, creating a sense of depth and complexity.

Probing the Structure of Matter

A History of Fundamental Particle Physics

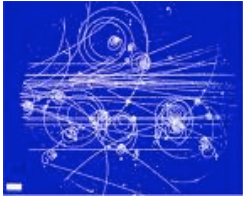
Steve Schnetzer
Rutgers University



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

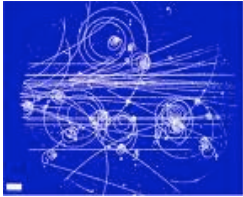


Constituents

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

Theory

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

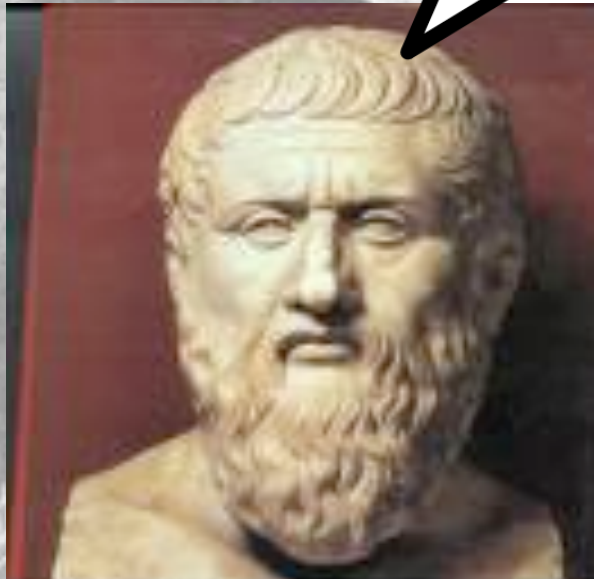


Ancient Greece

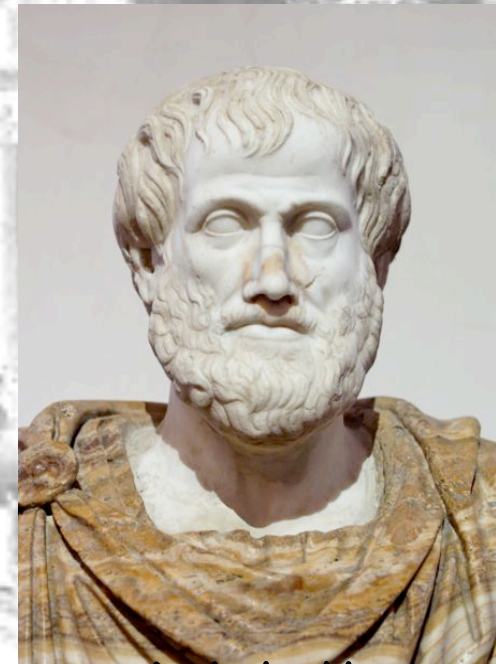


All is
mathematical
form

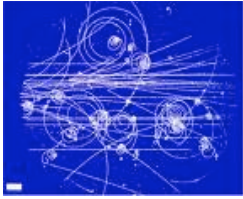
I can figure
out the universe
by pure thought



Plato



Aristotle



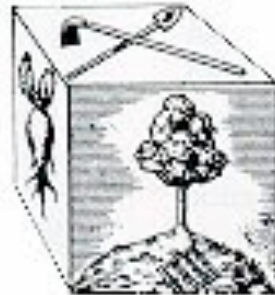
Fundamental Physics



Circa 500 B.C.



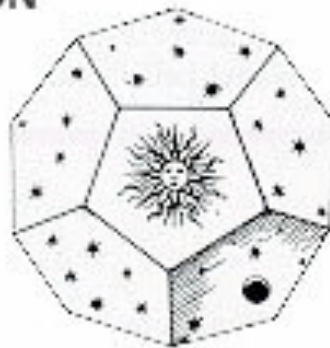
OCTAHEDRON
Air



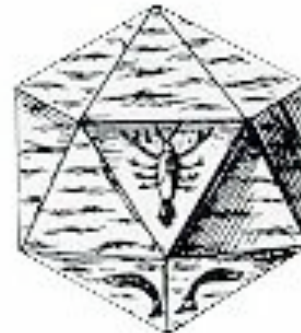
CUBE
Earth



TETRAHEDRON
Fire



DODECAHEDRON
the Universe



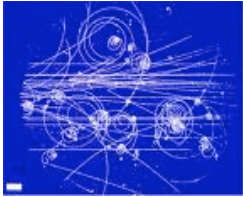
ICOSAHEDRON
Water

PSST!
The universe
is made up
of atoms



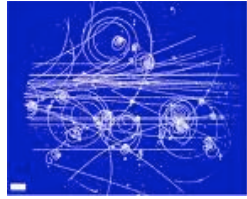
Democritus

The universe is built on
the five Platonic solids

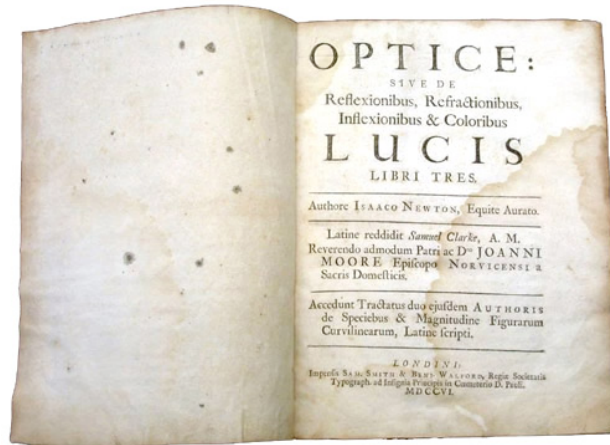


The Classical Period

1687 – 1897

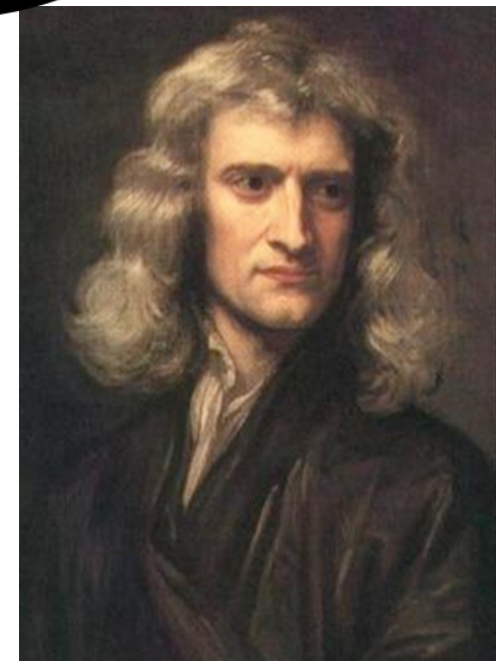
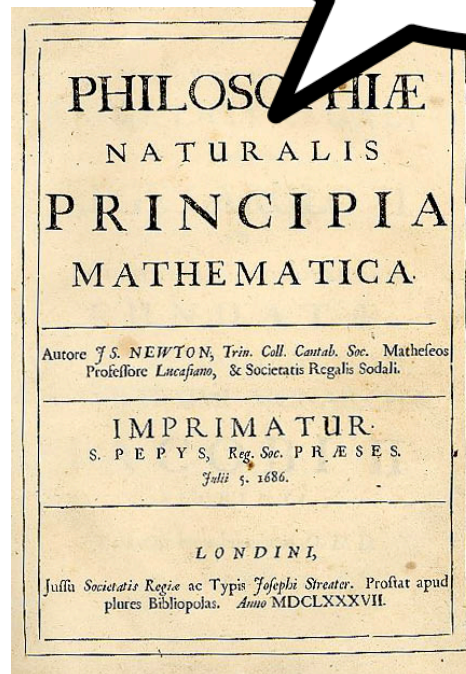
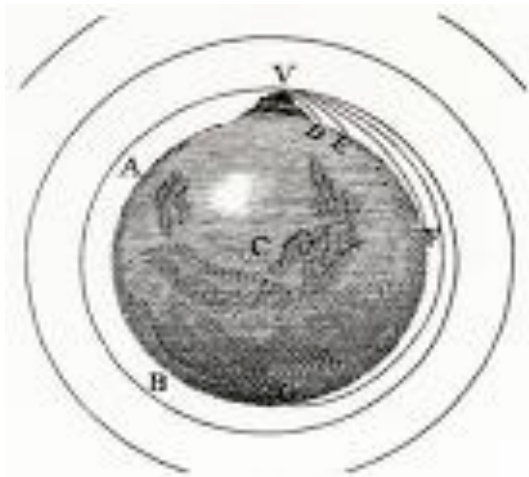
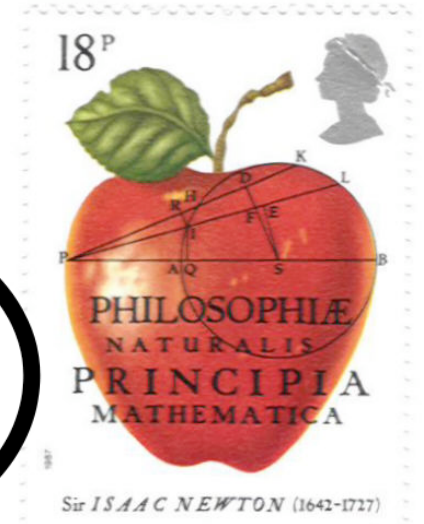


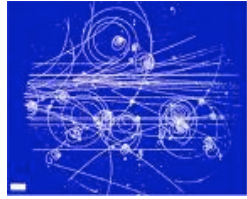
Newton



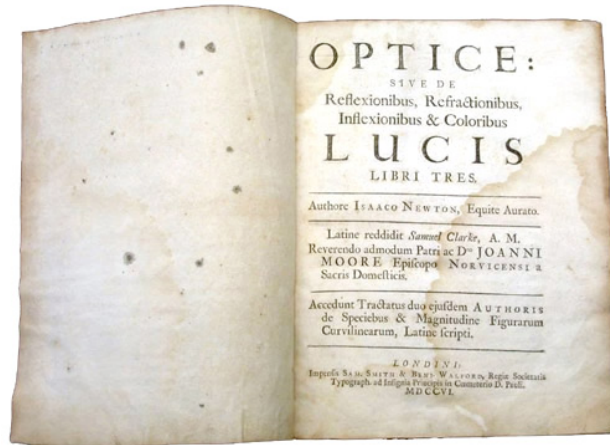
$$F = ma$$

The world is made of point particles



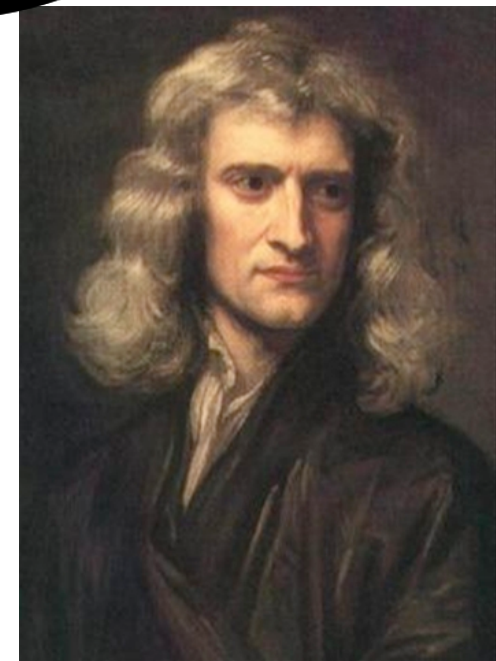
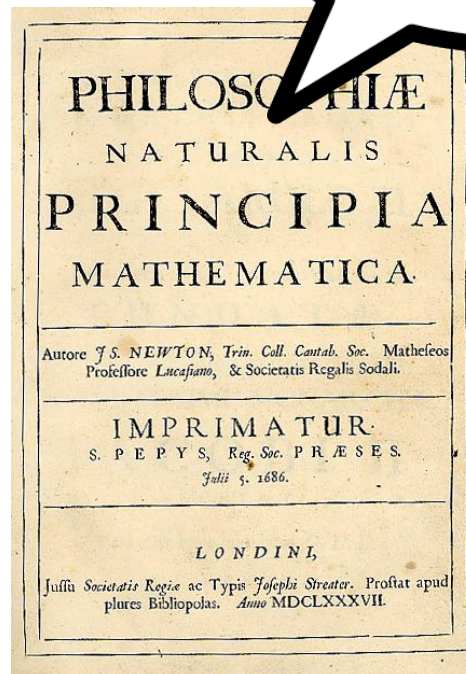
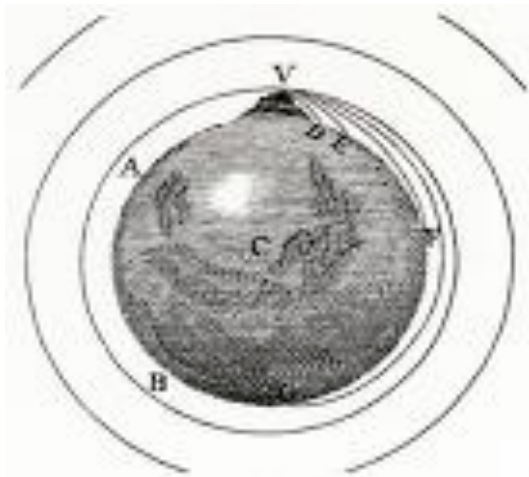
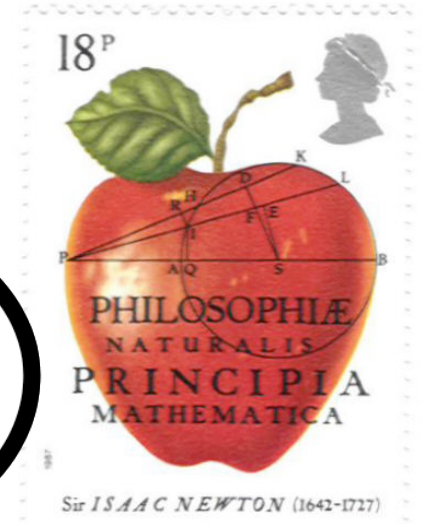


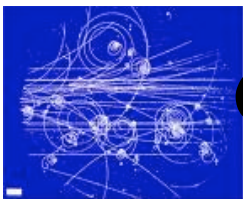
Newton



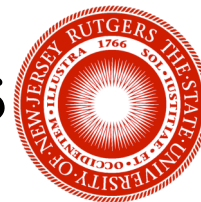
$$F = ma$$

I have no idea what they are





Chemists Discover Evidence for Atoms

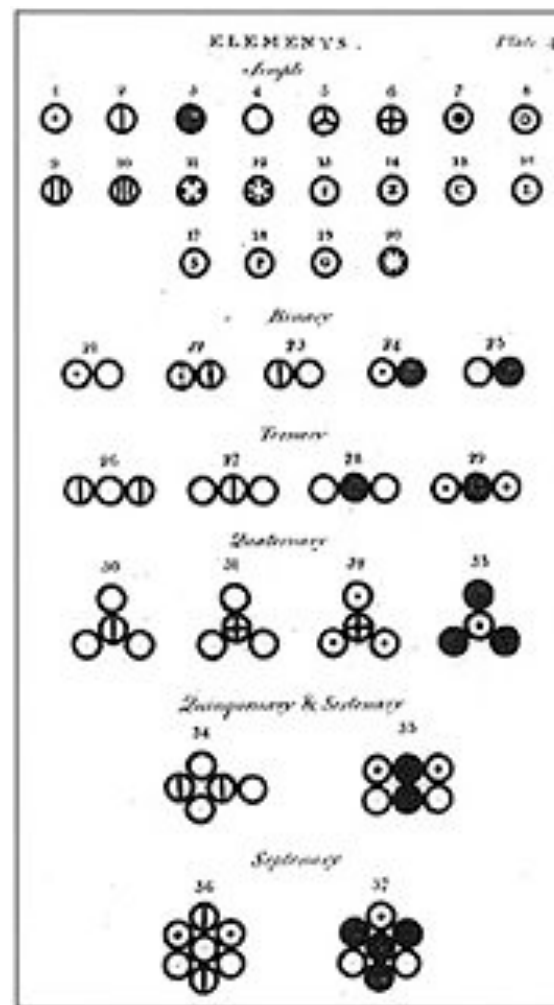
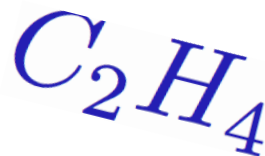


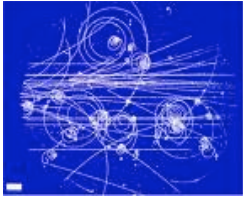
1802



John Dalton

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





World's First Particle Physicist



1827

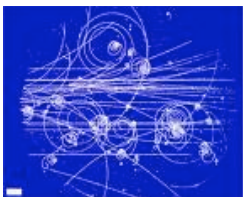
Discovered Brownian Motion



Robert Brown

Botanist

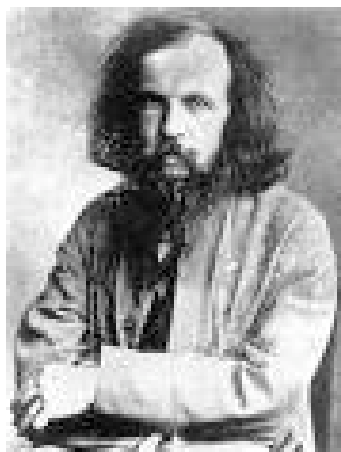




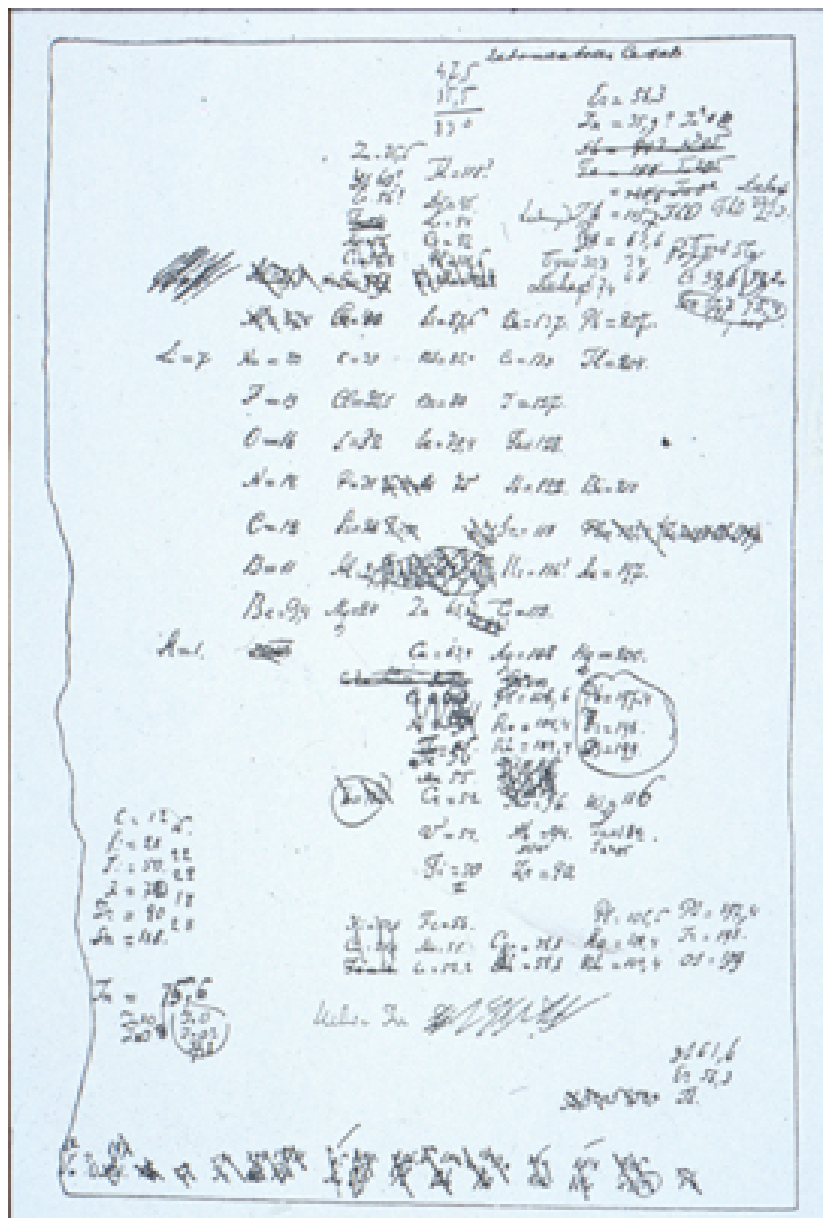
Periodic Table

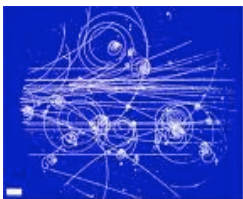


1869



Mendeleev





Fundamental Particle Physics



End of 19th century

92 Atoms

Periodic Table of the Elements

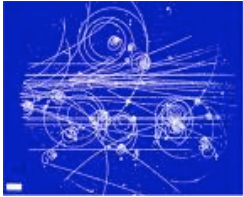
IA																	0					
1	H																		He			
		IIA															IIIA	IVA	VA	VIA	VIIA	
2	3 Li	4 Be															5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg	IIIB	IVB	VB	VIB	VII B	VII		IB	IIB	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar					
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr				
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe				
6	55 Cs	56 Ba	*La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn				
7	87 Fr	88 Ra	+Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110	111	112	113									

* Lanthanide Series

58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

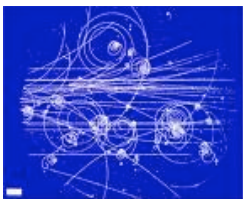
+ Actinide Series

90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

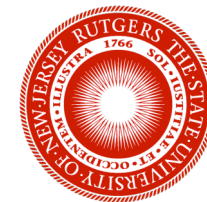


The Romantic Period

1897 – 1932



The Cavendish



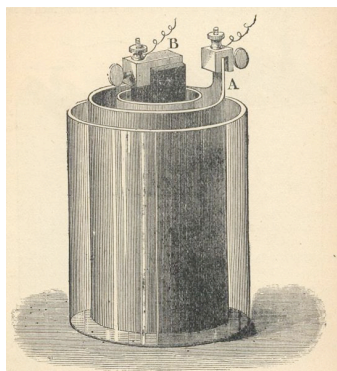
World's premier physics laboratory late 19th century



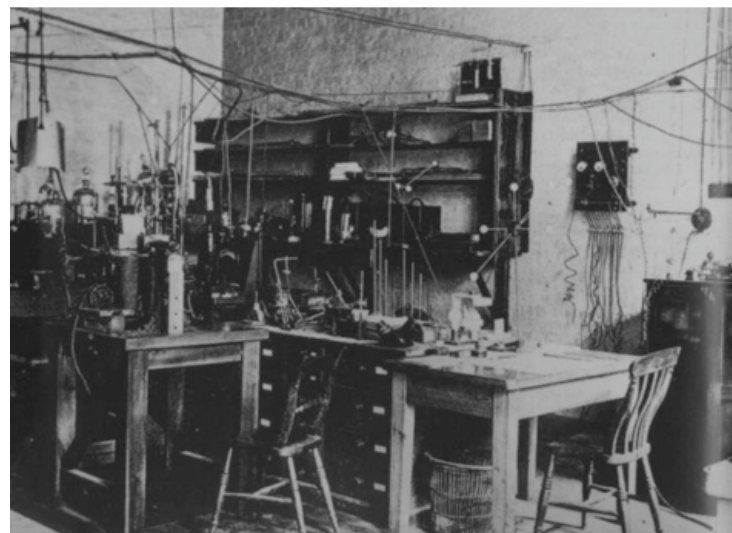
Cambridge University



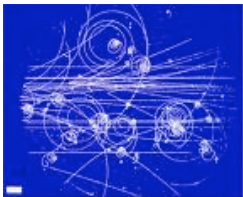
The Cavendish



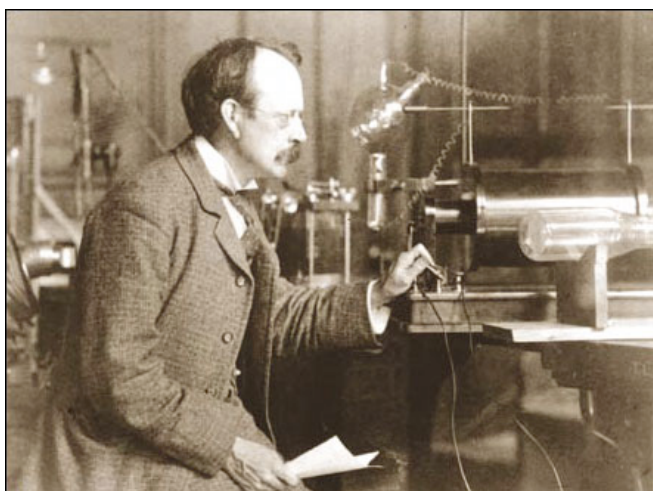
Bunsen Cell



A Typical Lab



Discovery of the Electron

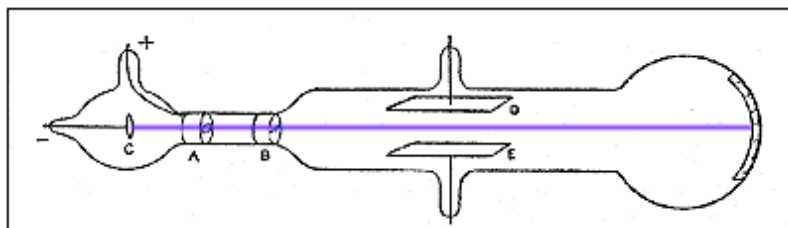


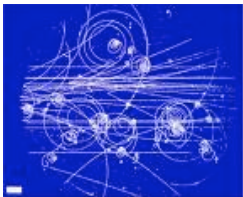
J. J. Thomson



Thomson's CRT

A new particle
electrically charged





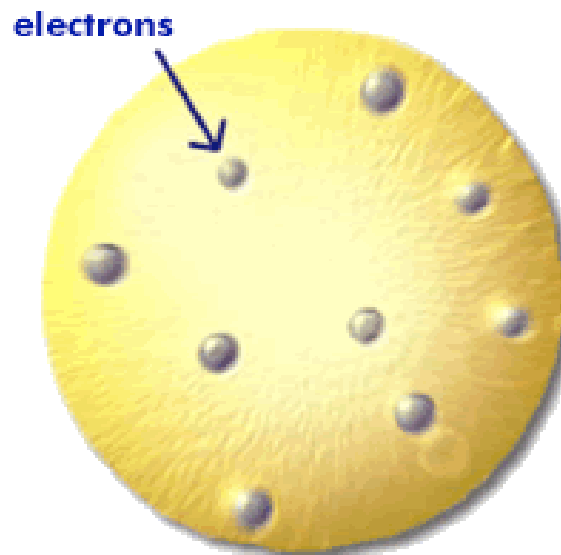
The Plum Pudding Model



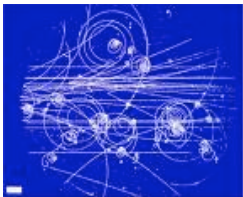
can knock electrons out of atoms (photoelectric effect)
⇒ electrons are a part of atoms

How to make a stable
electrically neutral atom?

negatively charged electrons
distributed like raisins in a
positively charged “pudding”



sphere of positive charge

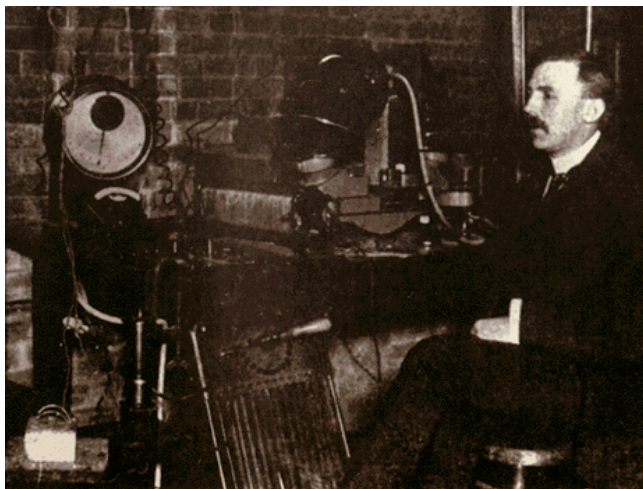


Lord Rutherford



World's first high energy physicist

1910

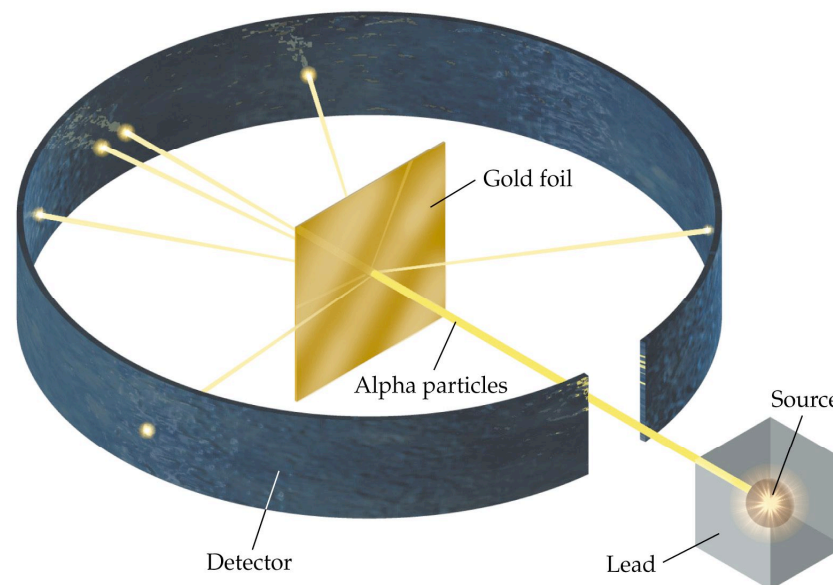


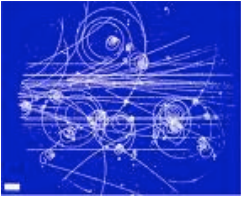
Ernest Rutherford

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"

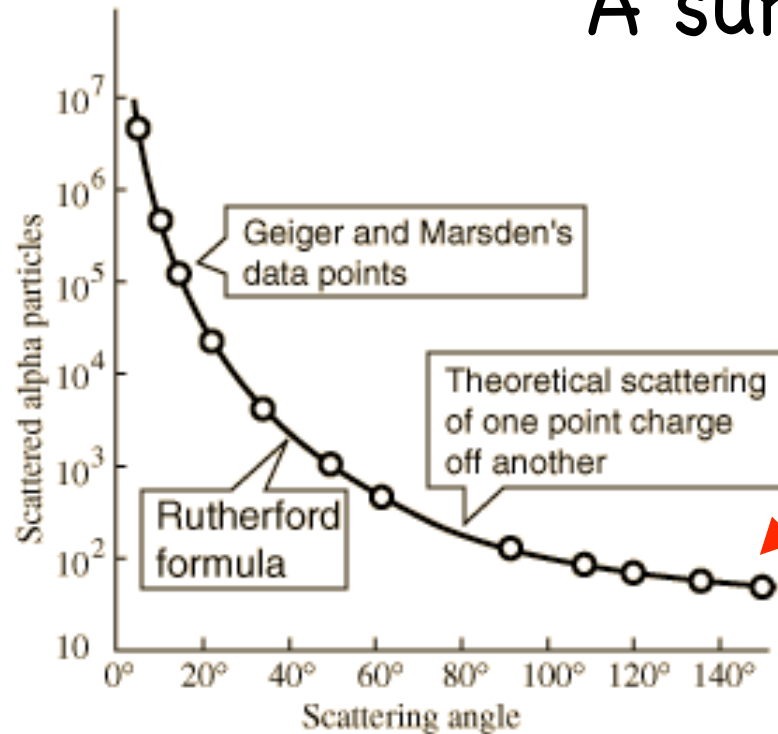




Rutherford Scattering



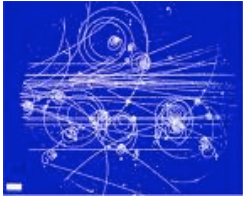
A surprise



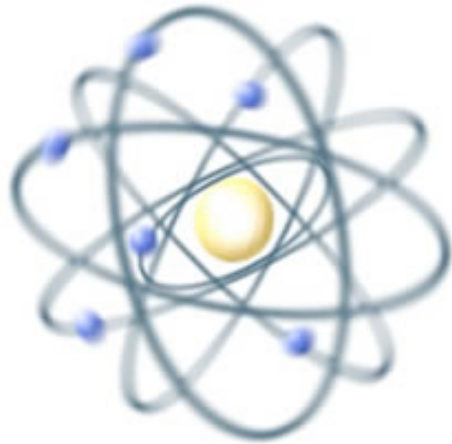
some of the alpha's scattered at large angles

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

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

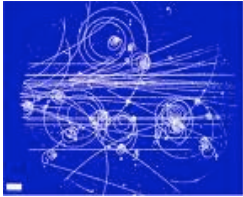


The Nuclear Atom



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

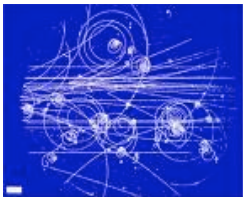
precision of
measurement

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

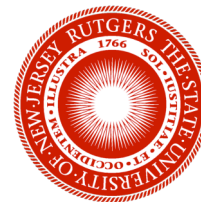
momentum
transferred

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



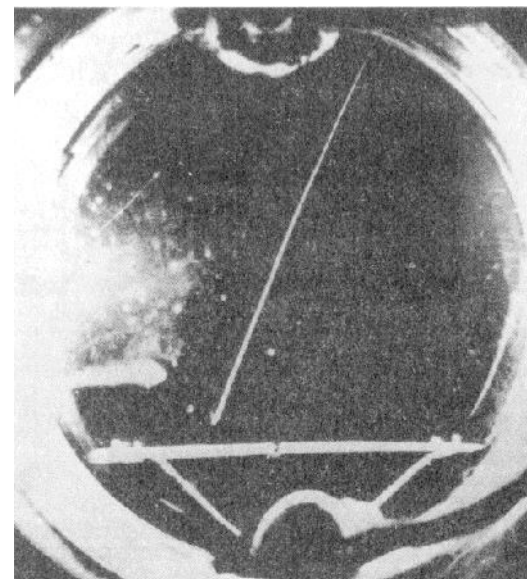
1932



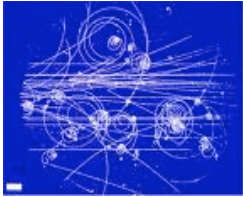
James Chadwick

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

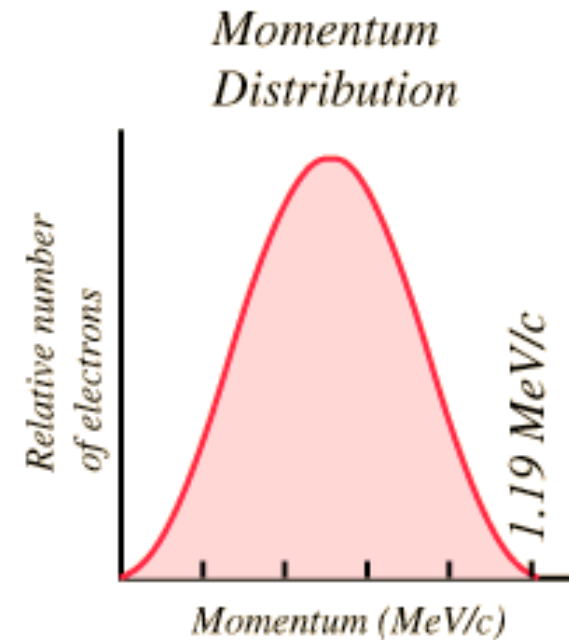
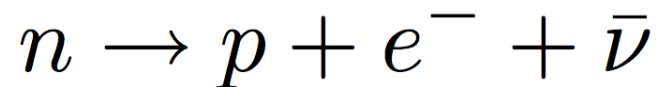


The Neutrino



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

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



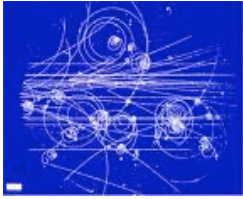
Ghost-like neutrino

Predicted in 1930 by Pauli

Discovered in 1956 by Cowan and Reines



Pauli



Fundamental Particle Physics



1932

neutrino

ν

electron

e^{-}

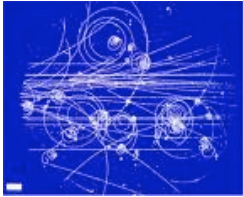
photon γ

proton

p

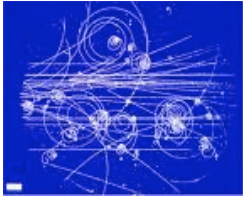
neutron

n



The Modern Period

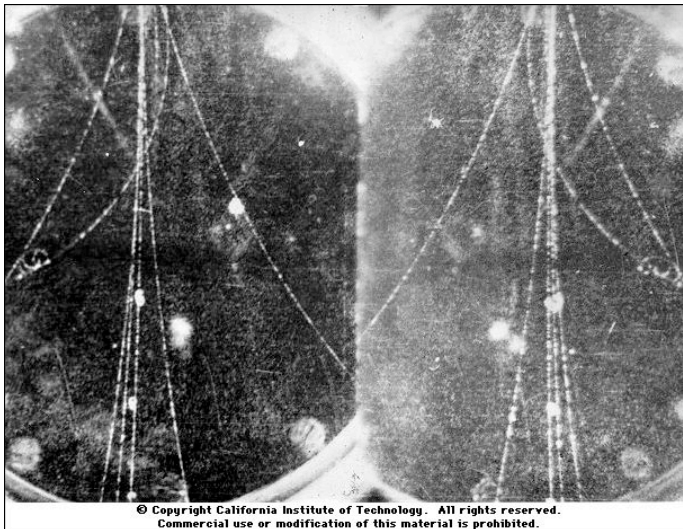
1932 – 1974



Cosmic Rays

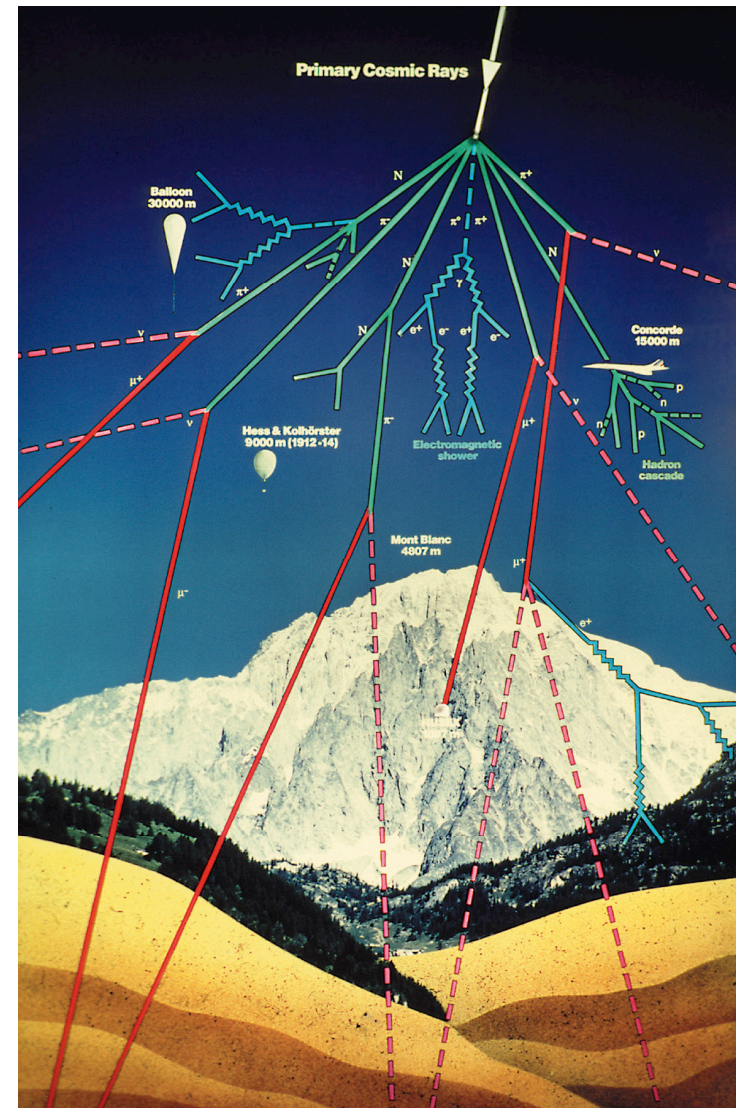


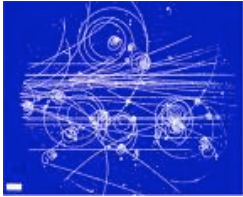
The cosmic accelerator
much higher energies
than available in the lab
with higher energies can
produce more massive particles



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cloud chamber





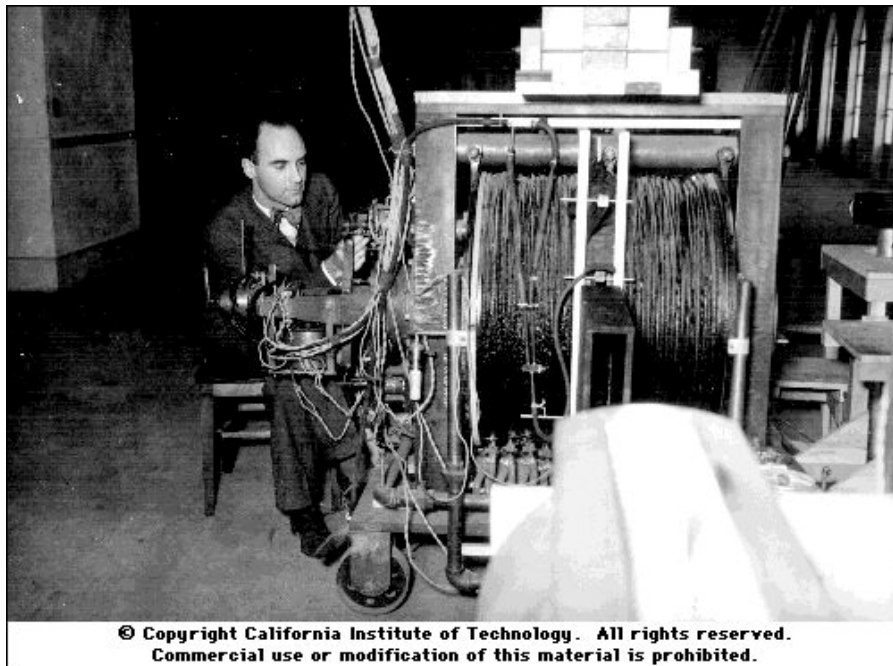
Antimatter



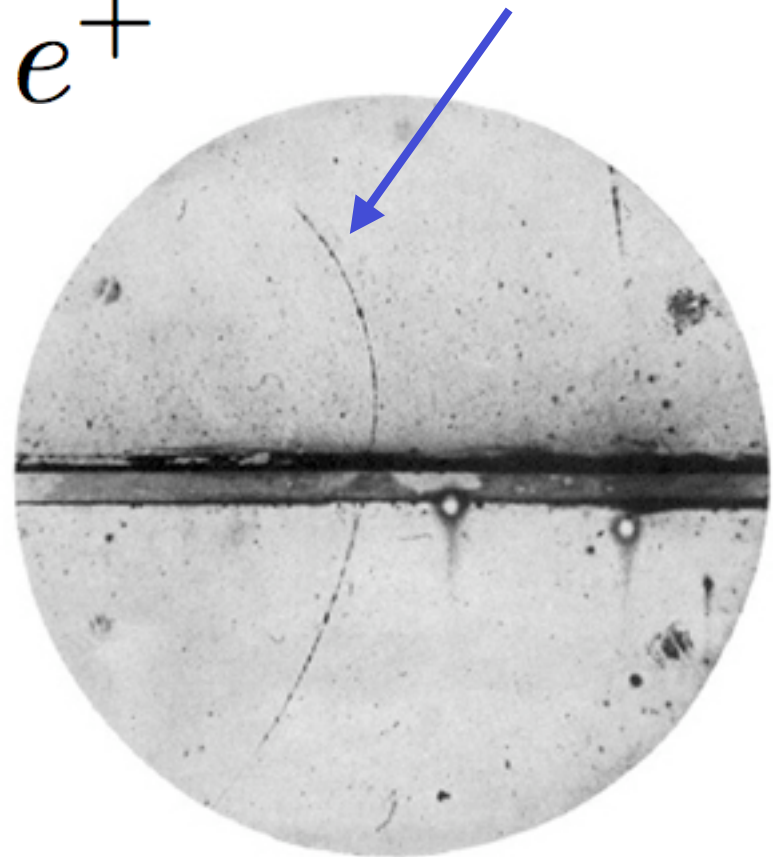
1932 Carl Anderson discovers
anti-electrons (positrons)

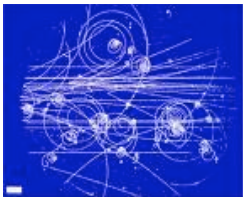
positron track

e^+

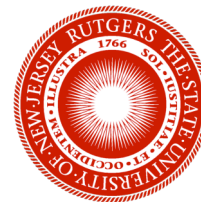


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Discovery of the Muon



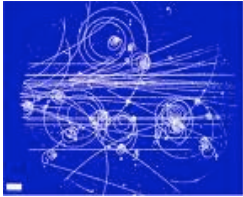
1937: the **muon** a heavy electron
discovered by Anderson

μ

Who ordered
that?

Just like electron
except about 200
times more mass

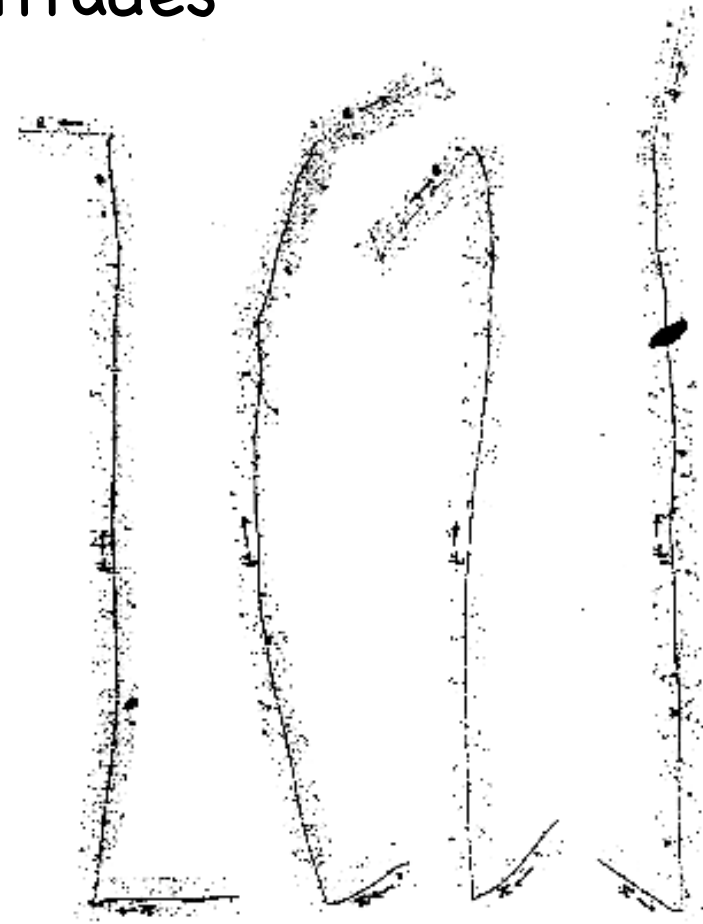
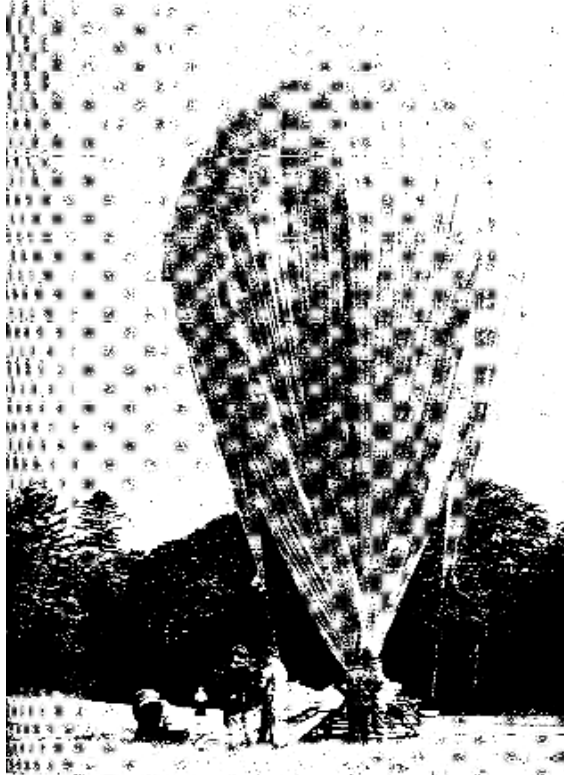


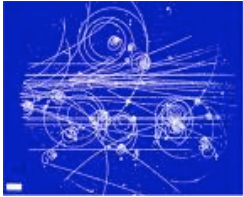


Particles Discoveries



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



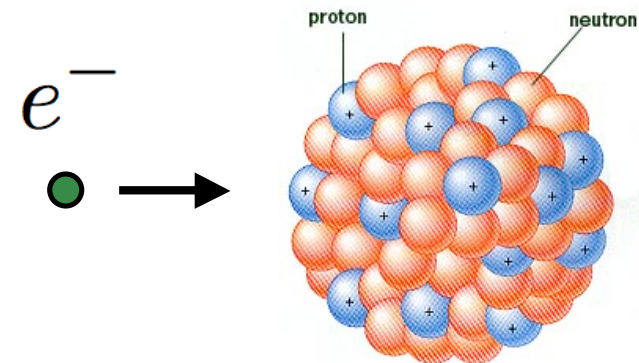


Structure of the Nucleus

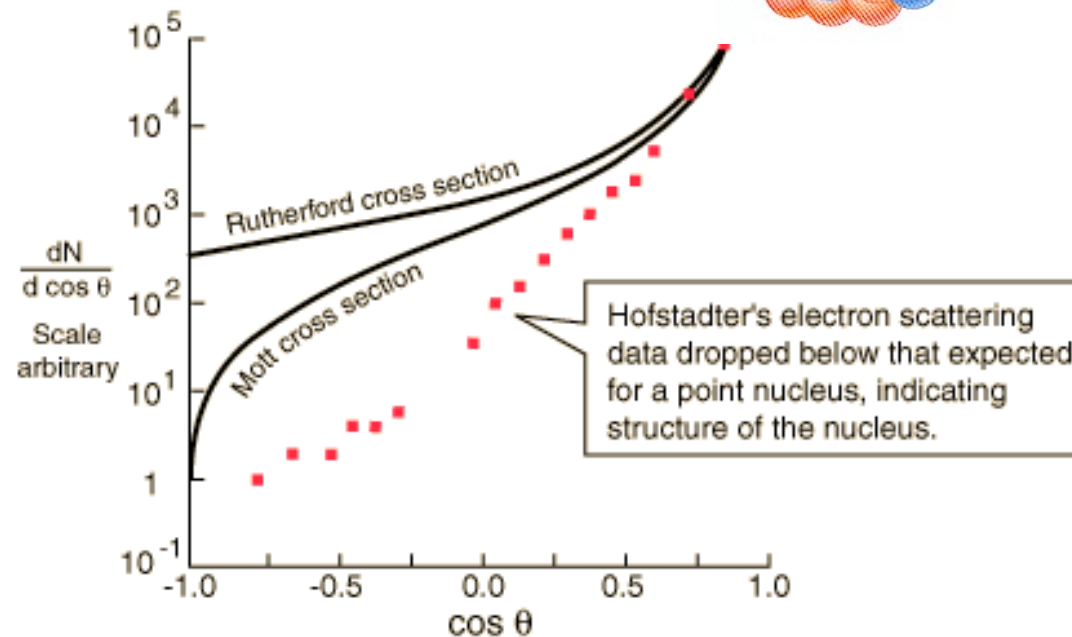


1953

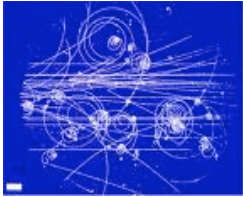
Scattered 125 MeV electrons off of nuclei



Hofstadter



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

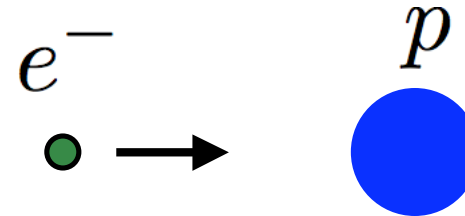


Structure of the Proton

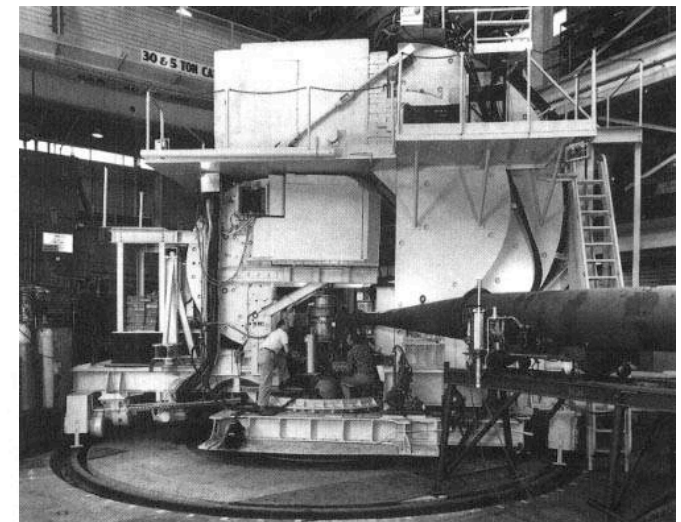
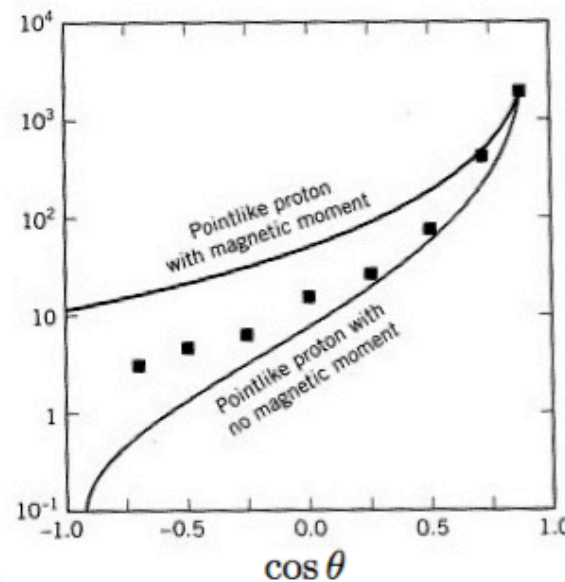


1956

Scattered 550 MeV
electrons off of nuclei

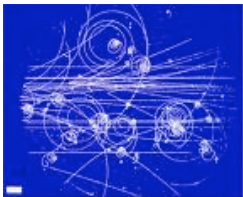


Mark 3 electron linac
at Stanford University



Hofstadter's spectrometer

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



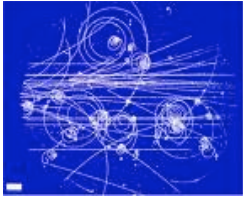
The Bevatron



6 GeV proton synchrotron
in the hills of Berkeley



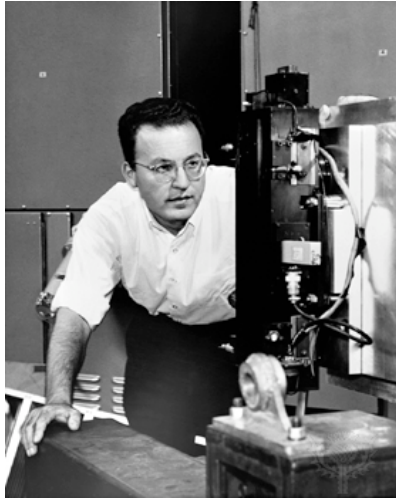
Designed to discover
the anti-proton



"Seeing" Particles



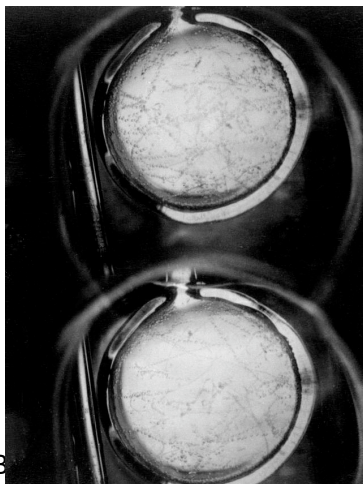
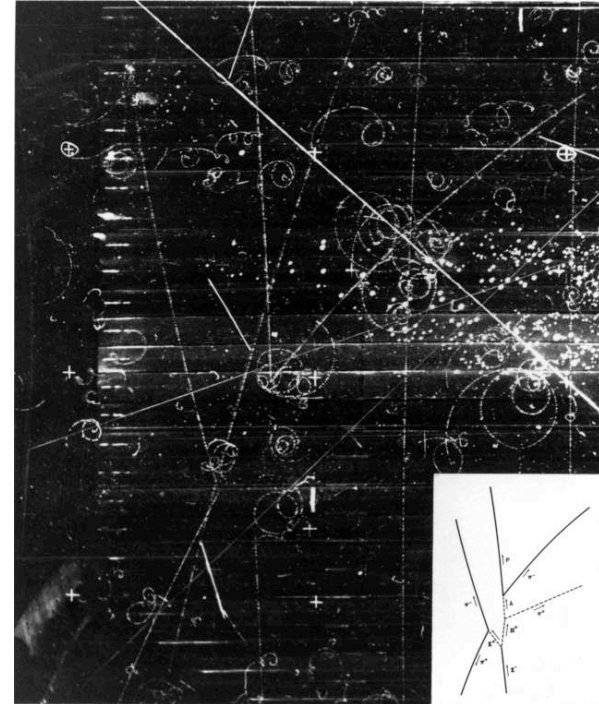
The bubble chamber

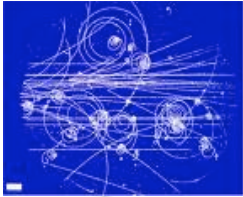


Donald Glaser



Luis Alvarez

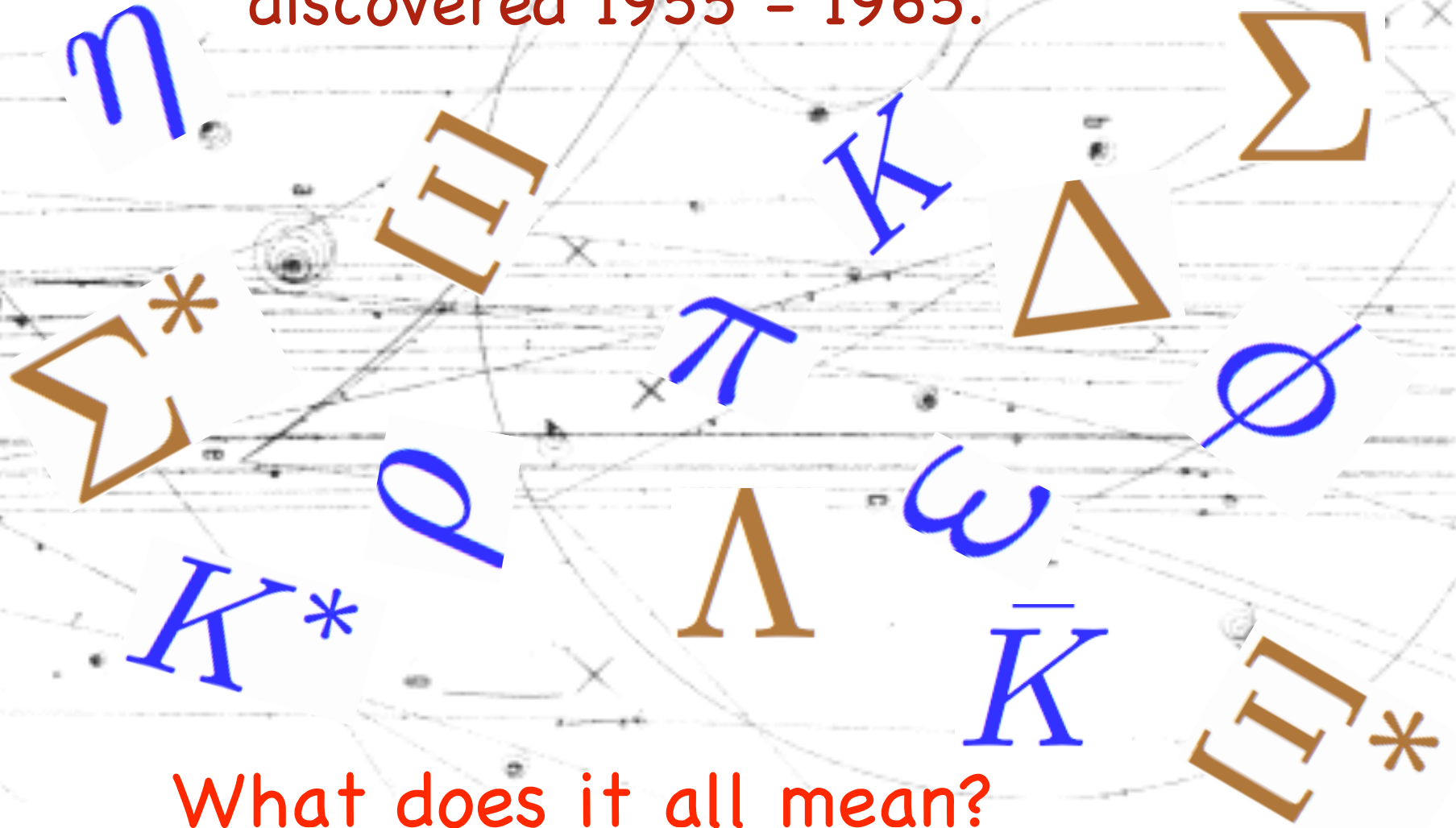




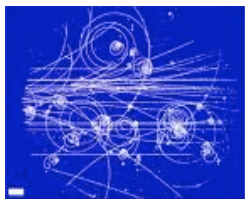
The Particle Zoo



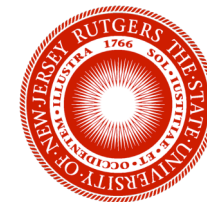
Hundreds of new particles
discovered 1955 - 1965.



What does it all mean?



Quarks



1964



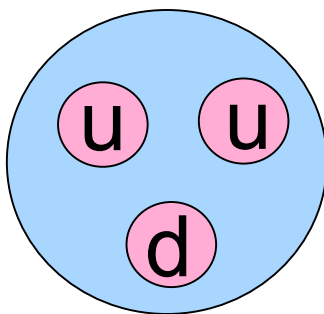
Murray Gell-Mann

Three quarks

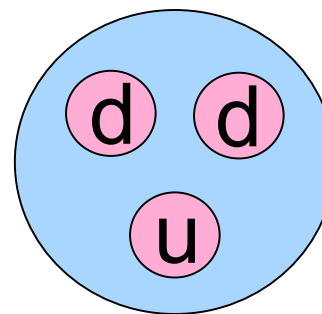
up down strange

mesons: $q\bar{q}$

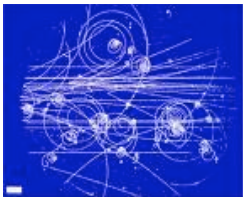
baryons: qqq



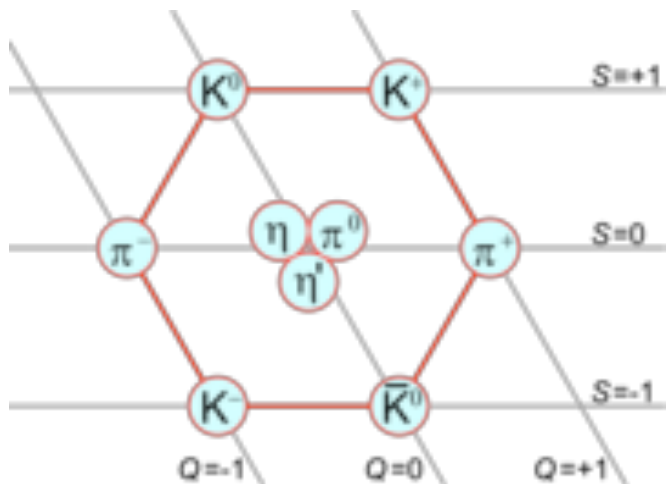
proton



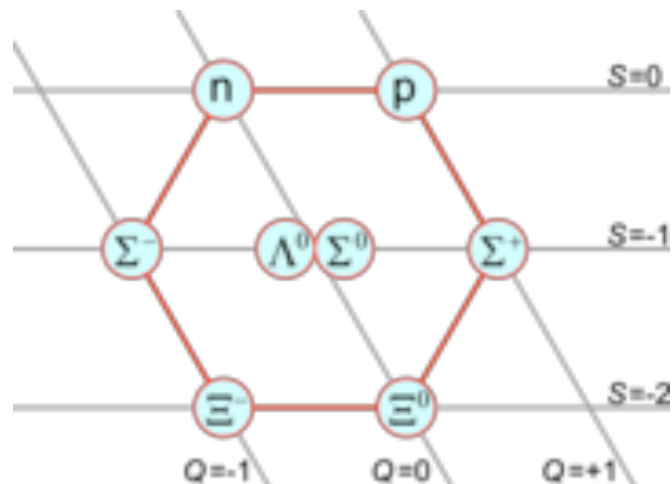
neutron



Classification Again



meson octet

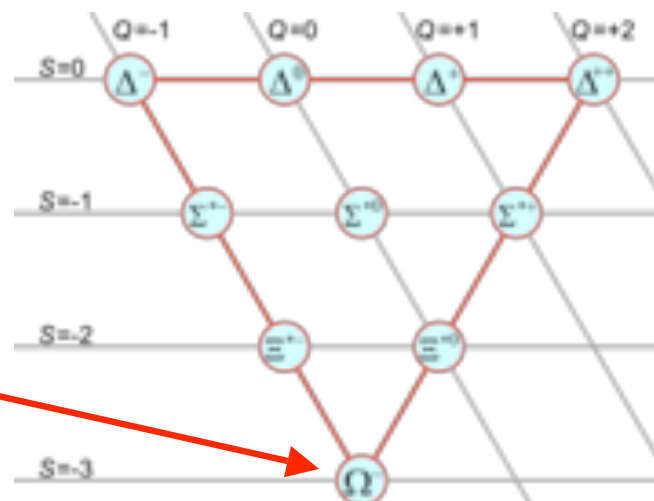


baryon octet

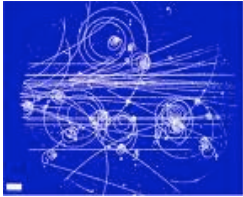
prediction:

Ω^-

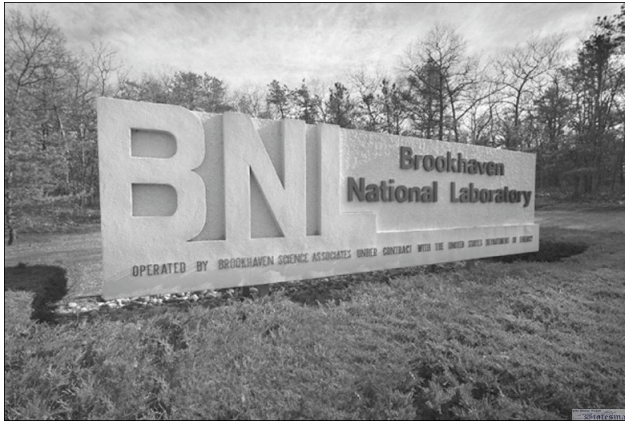
bound state of
3 strange quarks



baryon decuplet

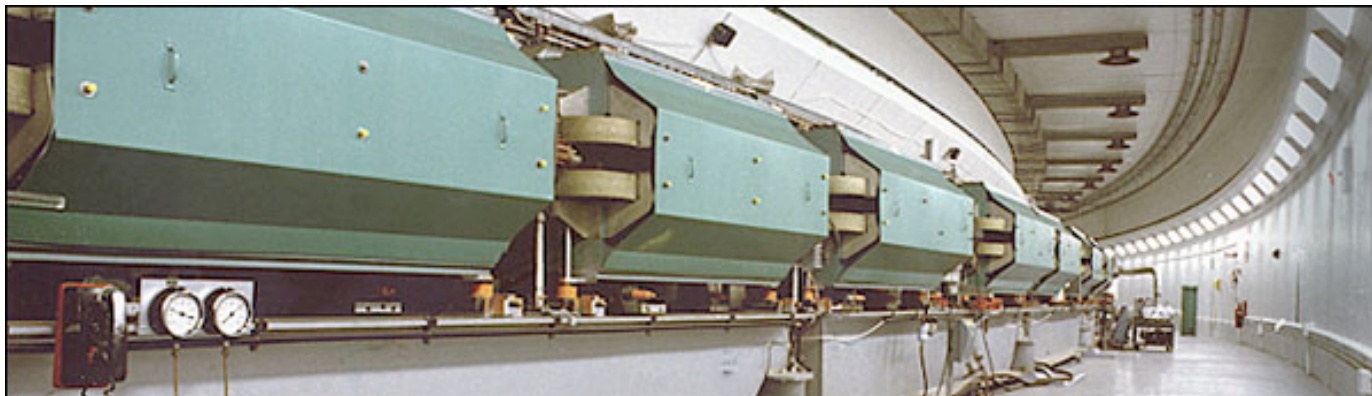


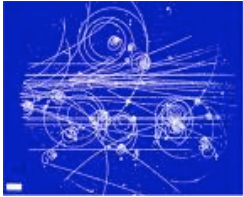
Brookhaven



The AGS

33 GeV proton synchrotron





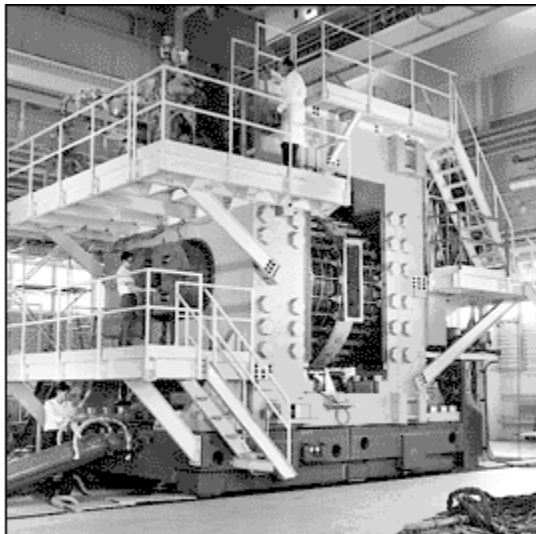
Discovery of the Omega Minus



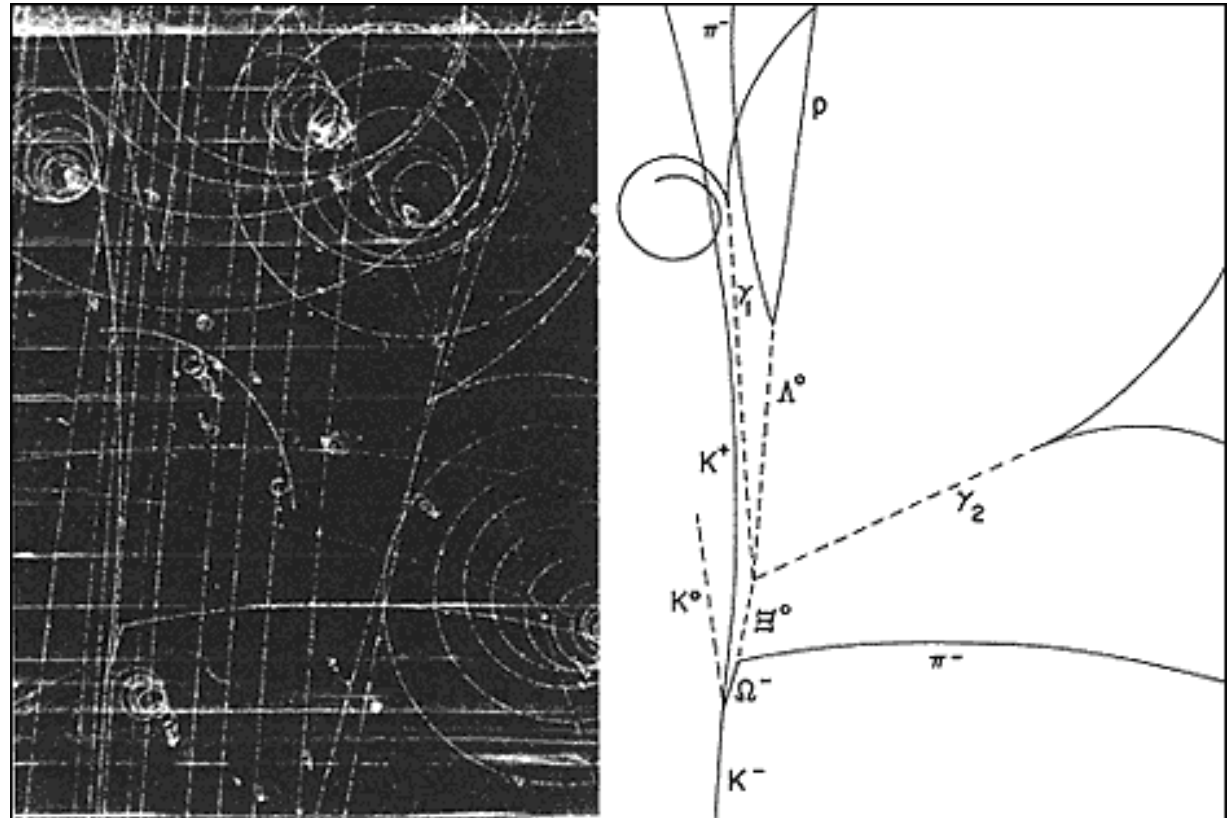
1964

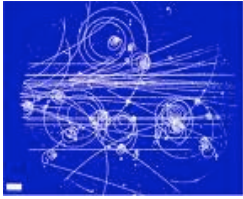


Nick Samios



80 - inch bubble chamber





Stanford Linear Accelerator Center



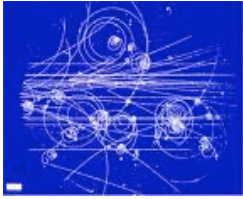
SLAC

30 GeV electrons



2-mile long linear accelerator



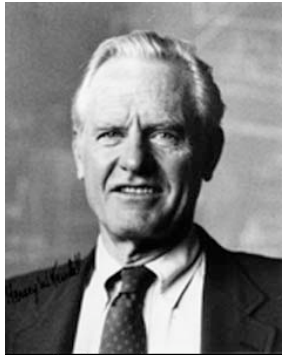


Inside the Proton

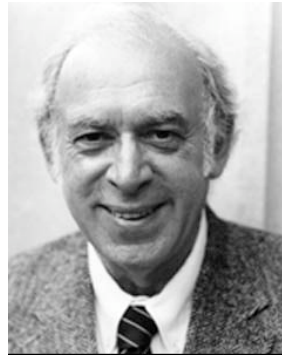


1968

SLAC - MIT Group



Kendall

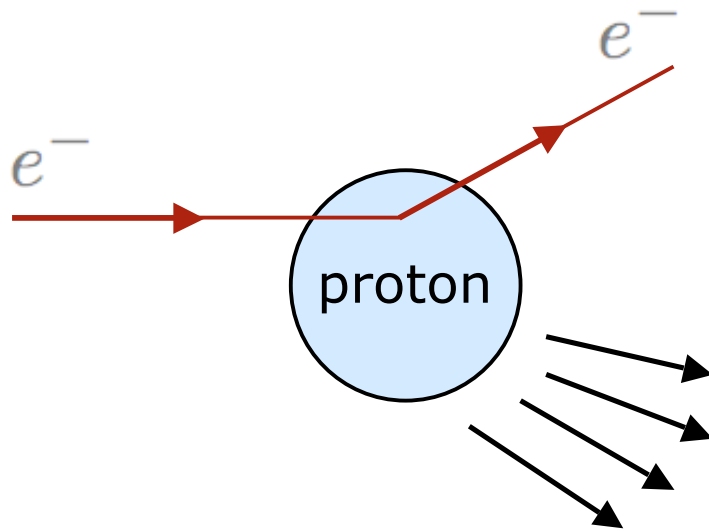


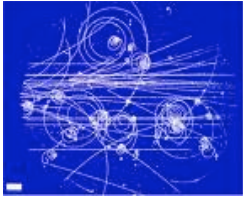
Friedman



Taylor

deep inelastic scattering





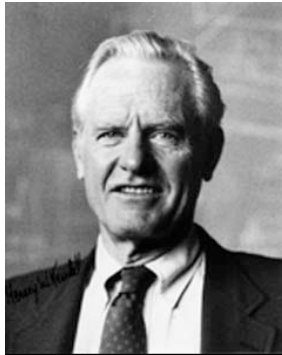
Inside the Proton



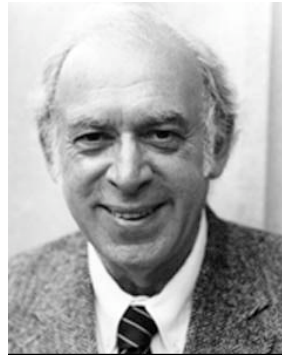
1968

SLAC - MIT Group

deep inelastic scattering



Kendall



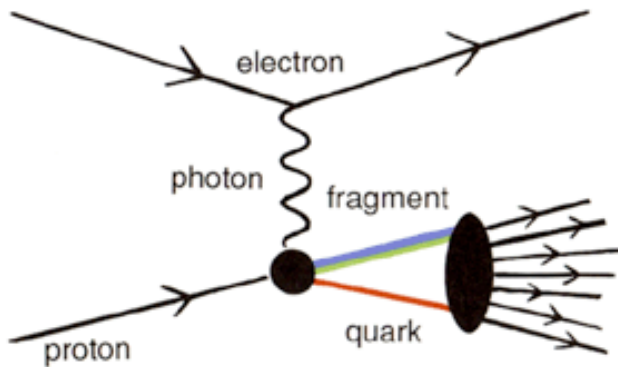
Friedman



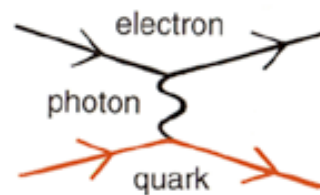
Taylor



Rutherford scattering off of point objects again

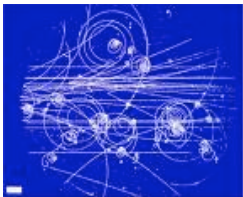


a



b





Fundamental Particle Physics



1974

leptons

ν_e

ν_μ

e^-

μ^-

gauge boson

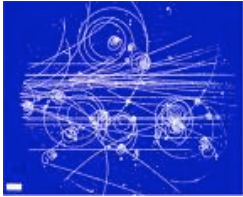
γ

quarks

u

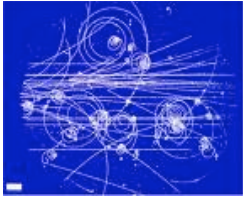
d

s



The Golden Period

1974 – 1982



Discovery of a New Quark



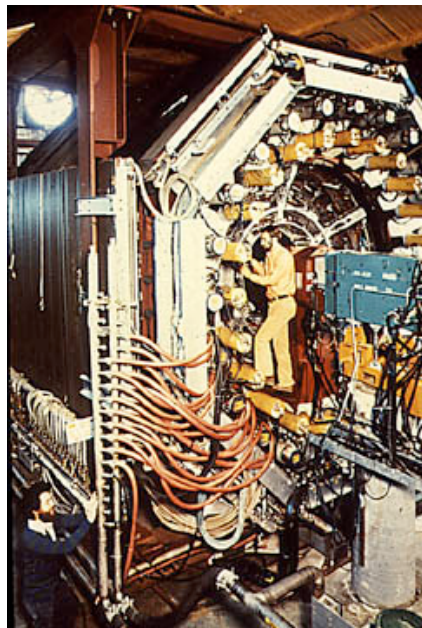
1974

resonance

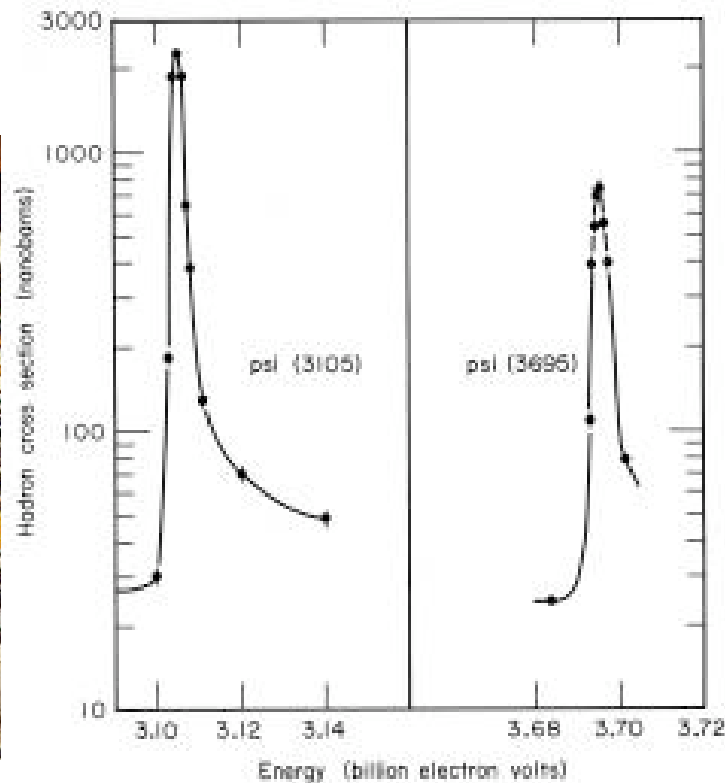


Burt Richter

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



NJAAPT Banquet
March 14, 2008



SPEAR

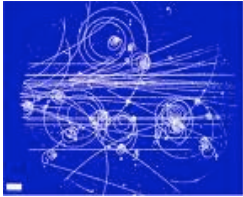
Electron-positron collider



J/ψ

bound state of **charm**
and **anti-charm** quarks

Charmonium



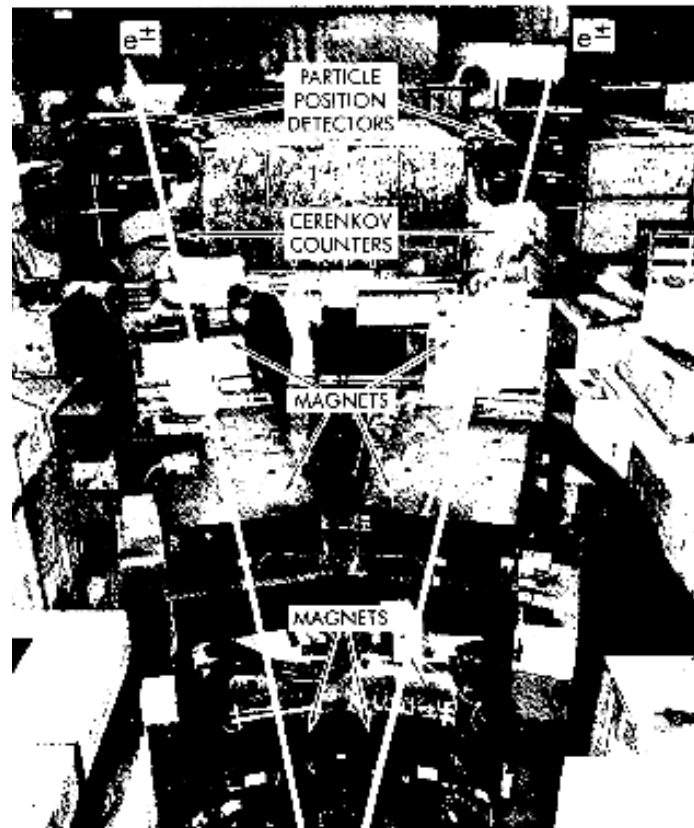
Simultaneous Discovery



Sam Ting

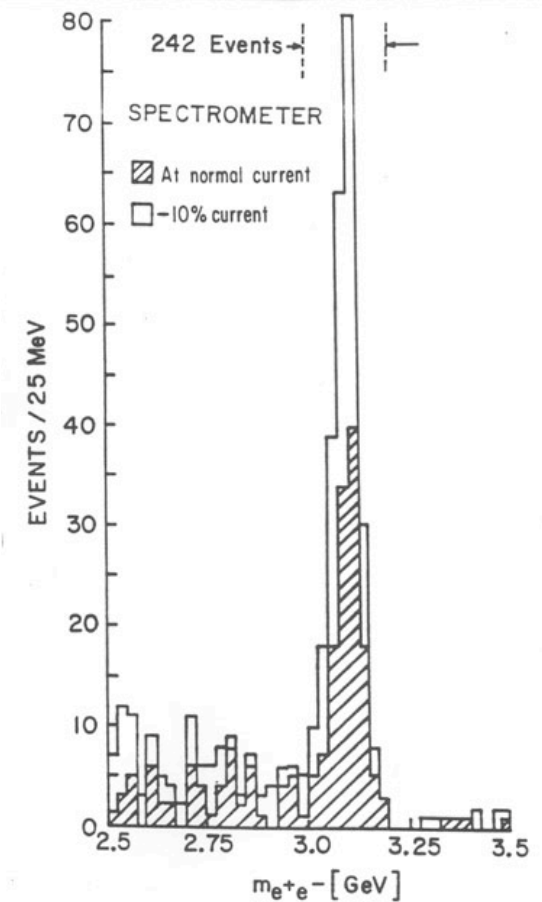
$$pp \rightarrow J/\psi + X$$

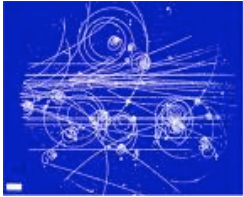
$$J/\psi \rightarrow e^+ e^-$$



Double-arm spectrometer

AGS Experiment



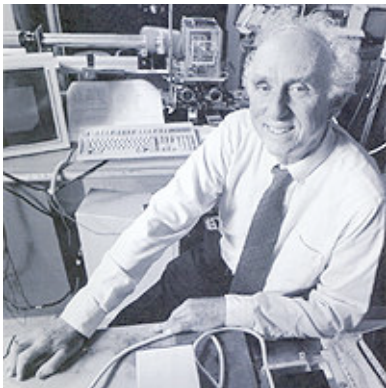


Discovery of a New Heavy Electron

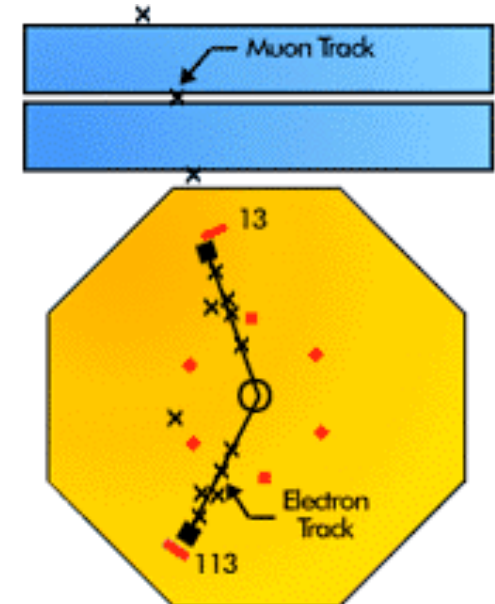
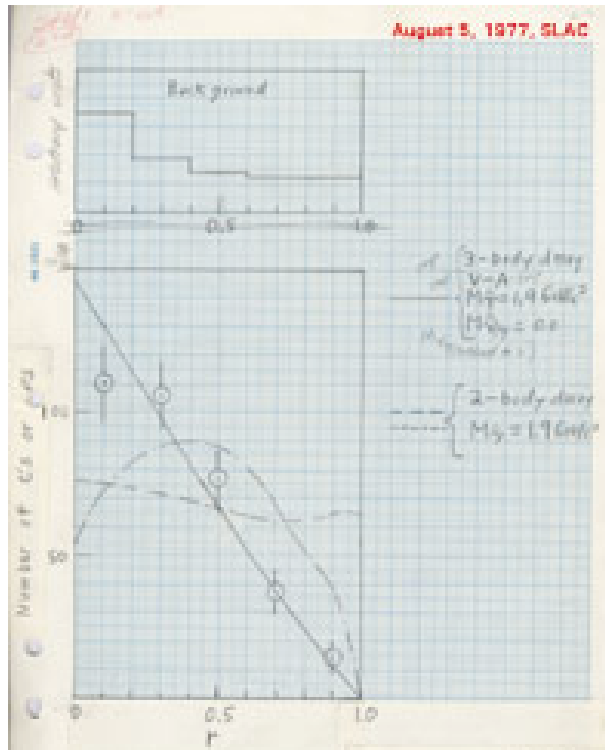
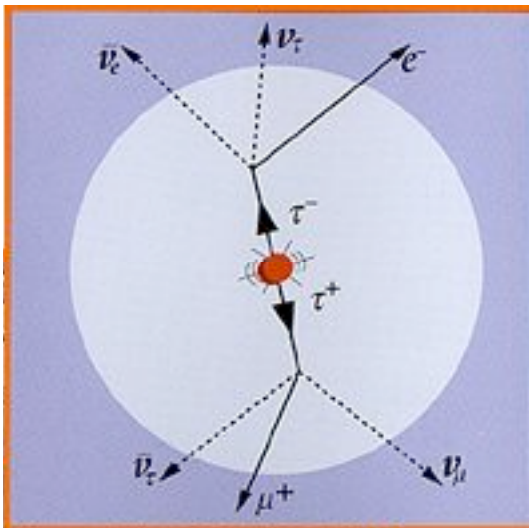
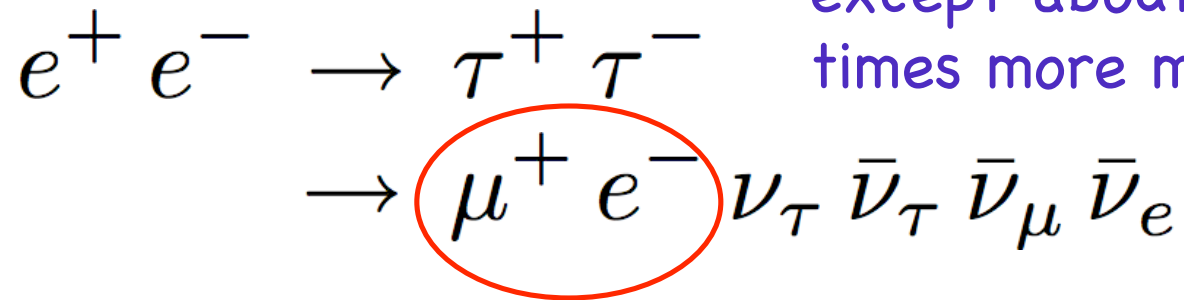


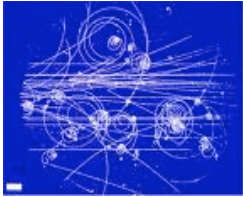
1975 The tau lepton

Just like electron
except about 2000
times more mass



Marty Perl





Fermilab

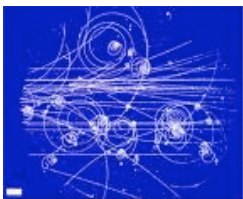


400 GeV Proton Synchrotron 2 km diameter ring



Robert Wilson





Discovery of Another New Quark



Leon Lederman

1976

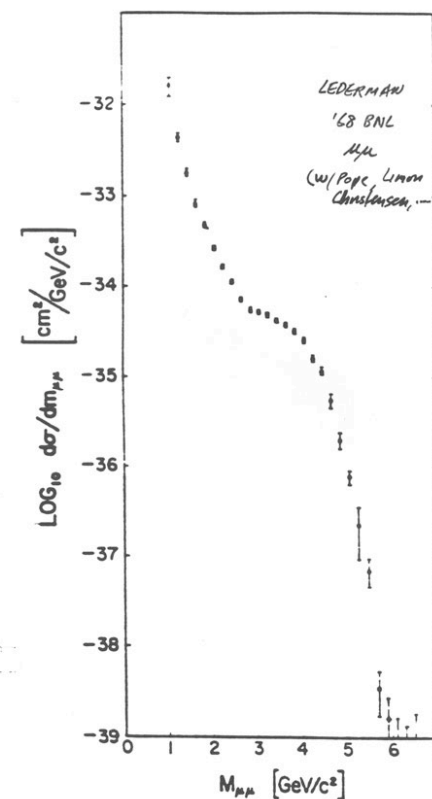
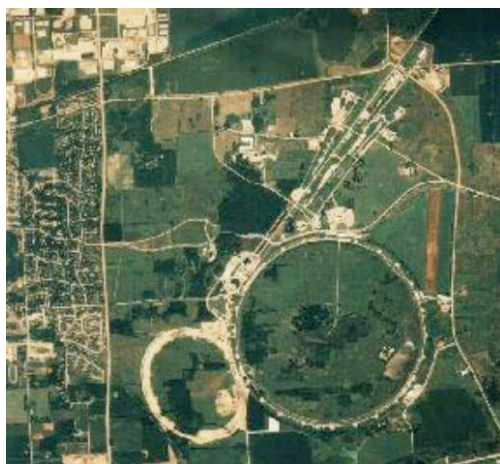
Υ

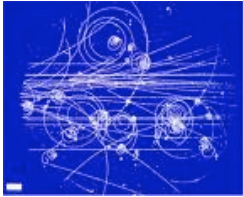
bound state of **bottom**
and **anti-bottom** quarks

$$pp \rightarrow \Upsilon + X$$

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

IN THE BEGINNING,





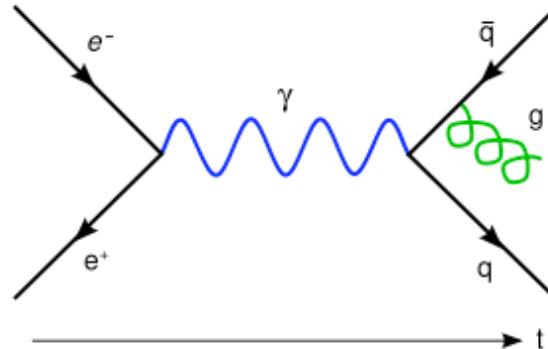
Discovery of the Gluon



1979



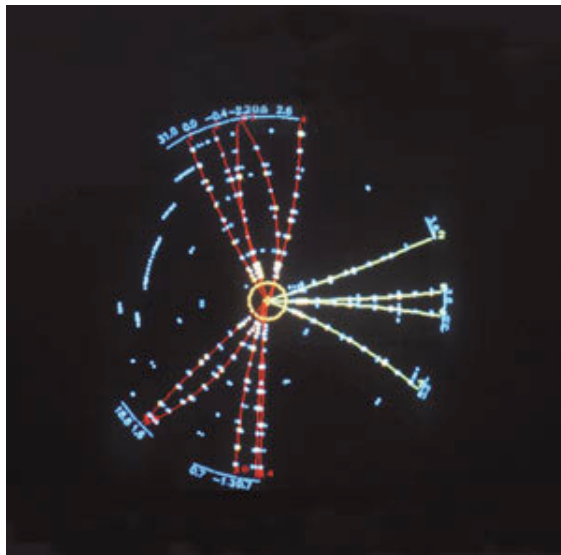
Sau Lan Wu



30 GeV e^+e^- Collider

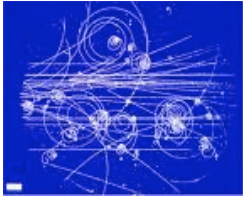


PETRA



carrier of the strong force
Quantum Chromo Dynamics

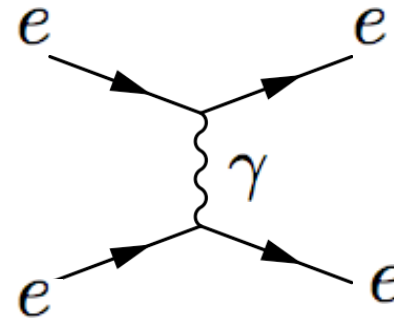
binds quarks together
to make proton



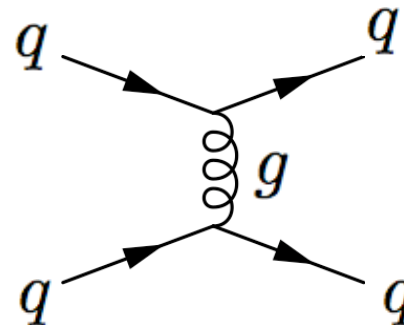
The Standard Model



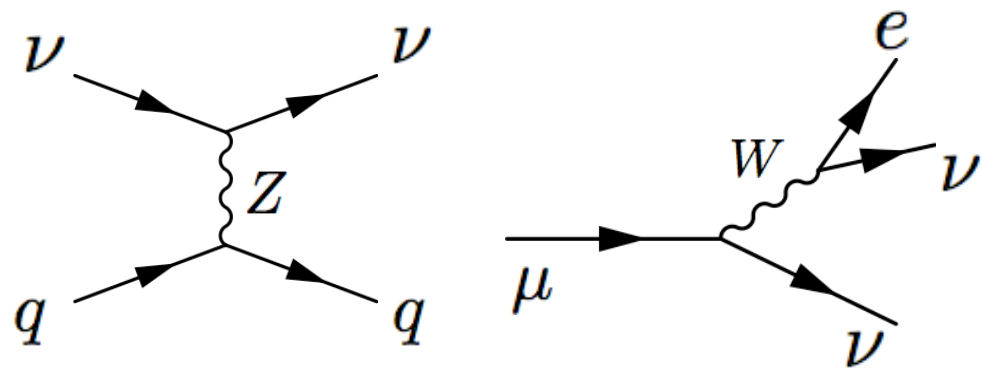
Quantum Electrodynamics
charged particles interacting
by photon exchange
atomic physics

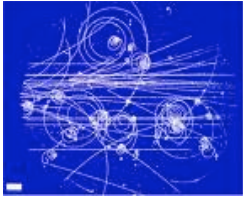


Quantum Chromodynamics
quarks interacting
by gluon exchange
binding of quarks



Weak Force
particles interacting
by W and Z exchange
heavy lepton decay
heavy quark decay
neutrino interactions





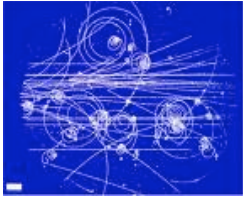
CERN



Off to the French Alps

proton – antiproton
collisions at 450 GeV





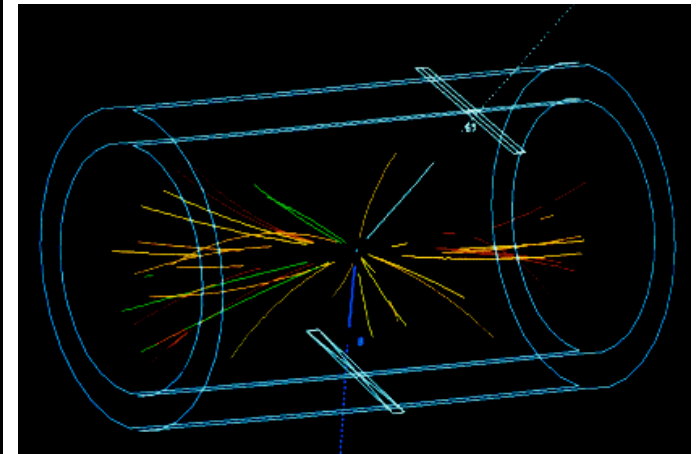
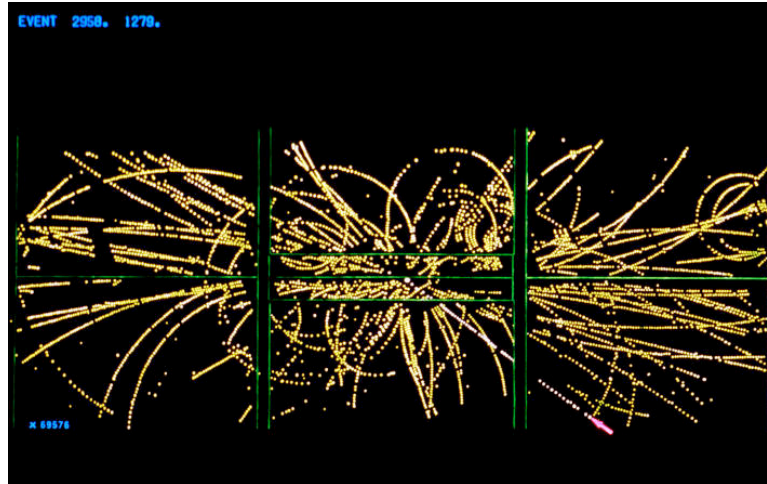
Discovery of the W and Z



1982



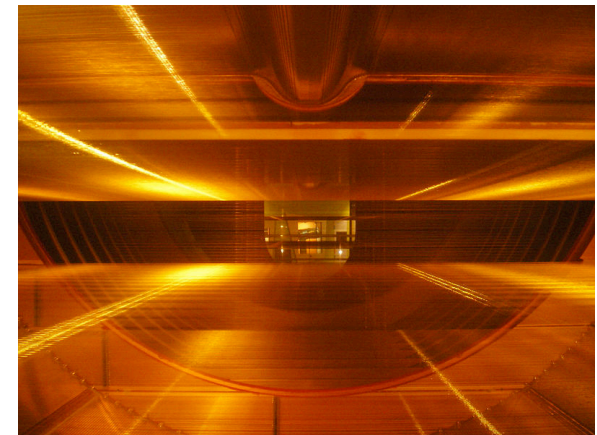
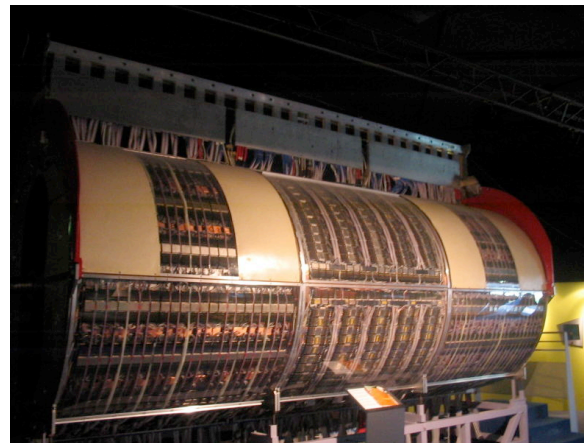
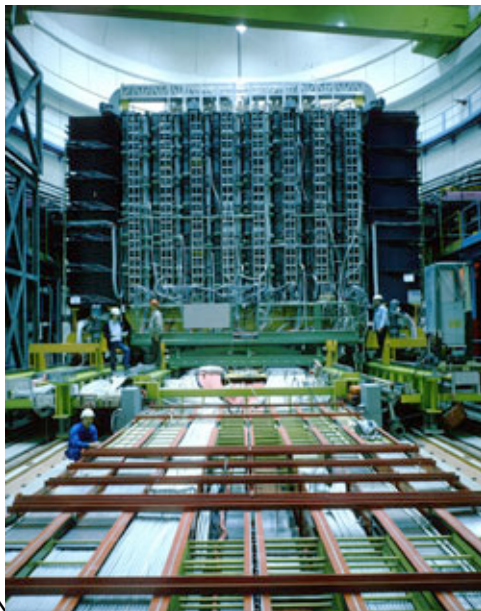
Rubbia



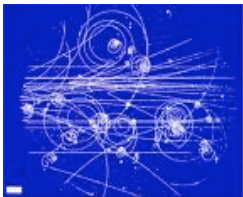
$$W \rightarrow e \nu$$

$$Z \rightarrow e^+ e^-$$

UA 1 Detector



Nobel Banquet
March 14, 2008



Fundamental Particle Physics



1982

leptons

ν_e ν_μ
 e^- μ^- τ^-

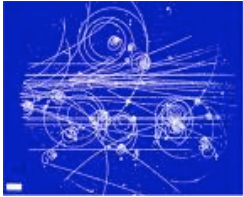
gauge bosons

γ
 g

quarks

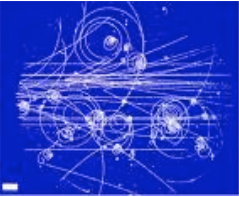
u c
 d s b

W^+ W^- Z^0



The Recent Period

1982 – 2008



LEP

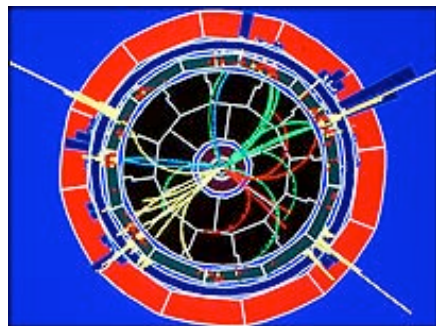
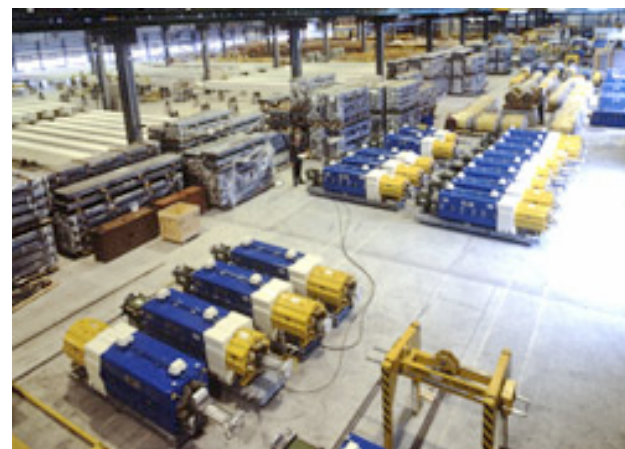


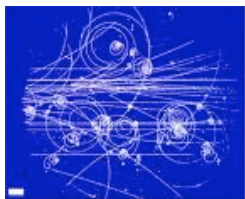
1989 - 2000

100 GeV electron - positron collisions at CERN



27 kilometer tunnel

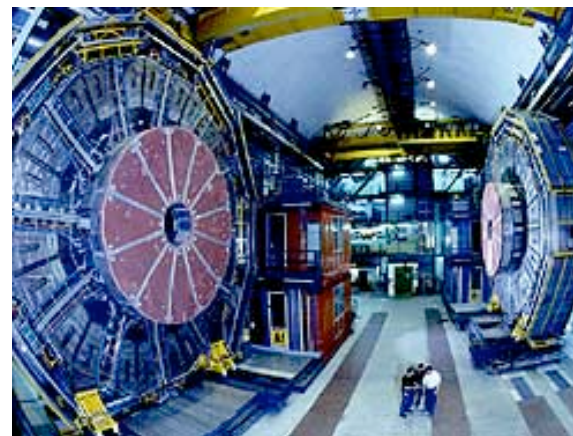




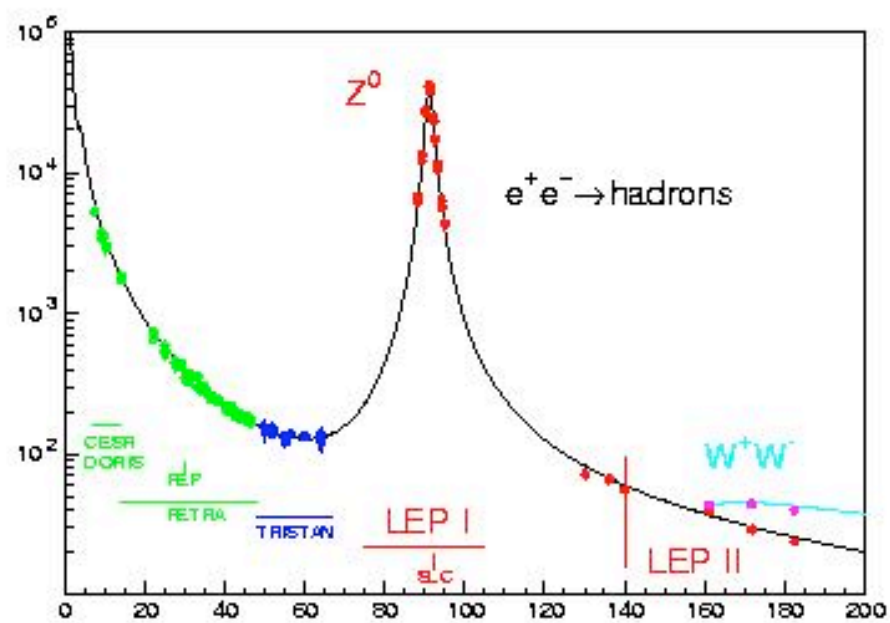
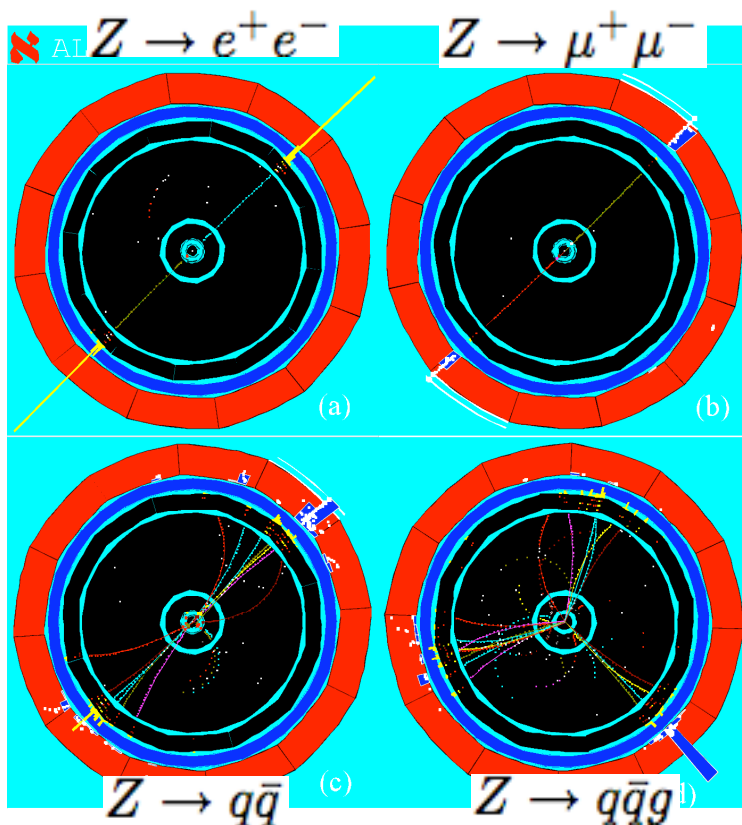
Z Factory

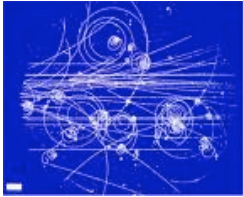


Over 10 million Z's produced and decays studied by four large detectors



Aleph Detector





Precision Tests of Standard Model



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

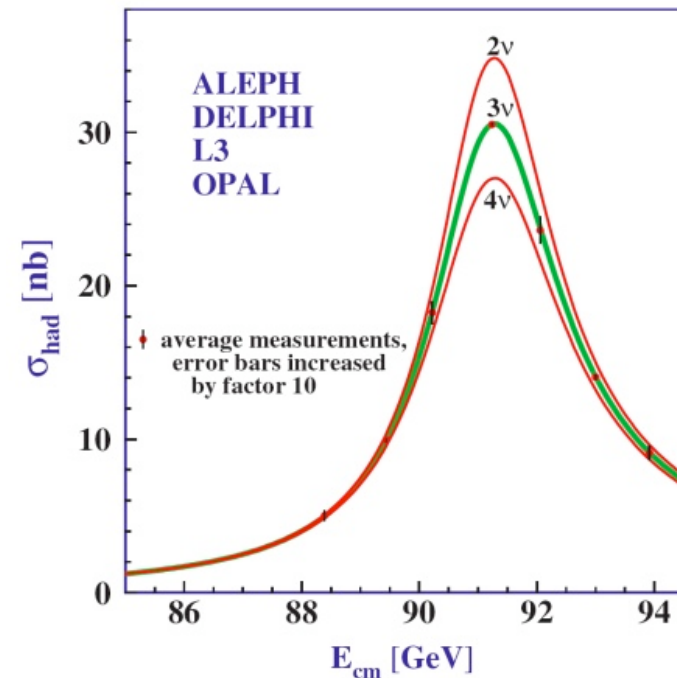
- Only three light neutrinos

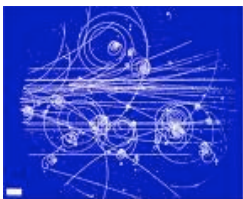
$$Z \rightarrow \nu\bar{\nu}$$

- 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

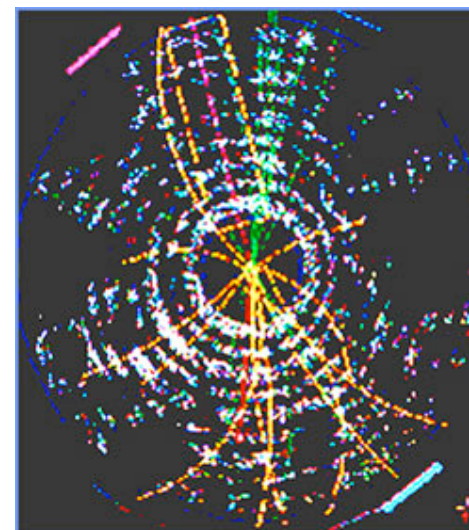
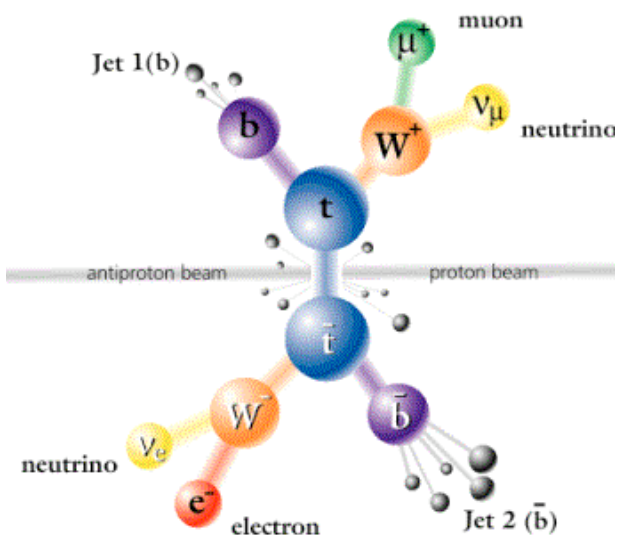
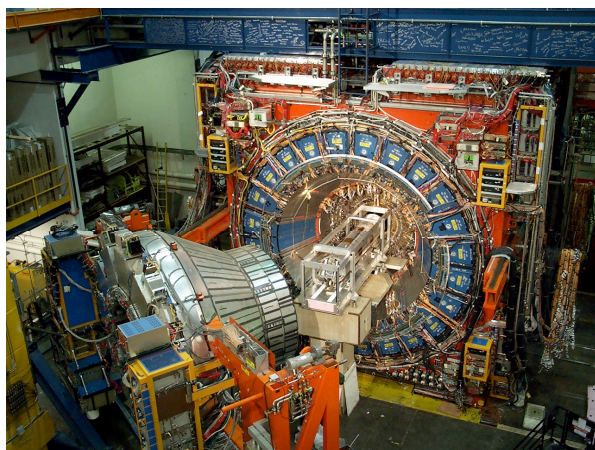


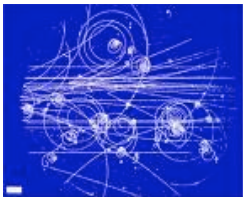
D0 Collaboration

Fermilab Tevatron Collider

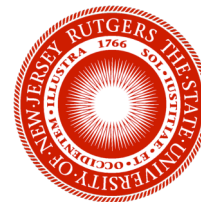


Production top anti-top





Fundamental Particle Physics



2008

leptons

ν_e ν_μ ν_τ
 e^- μ^- τ^-

gauge bosons

γ
 g

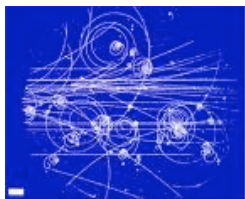
quarks

u c t
 d s b

W^+ W^- Z^0

Higgs

missing



Summary



Complete, consistent theory of fundamental physics

★ Fundamental constituents:

6 quarks and 6 leptons
plus antiparticles

★ Three fundamental forces:

Electromagnetic

mediated by
photons

Strong

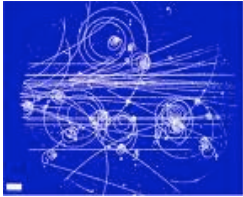
mediated by
gluons

Weak

mediated by
 W^+ W^- Z^0

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

★ Needs Higgs particle to be complete



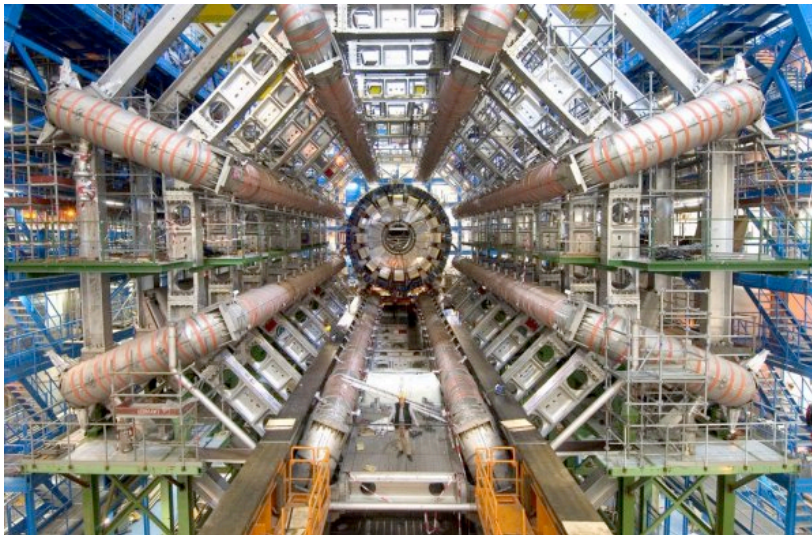
The Large Hadron Collider



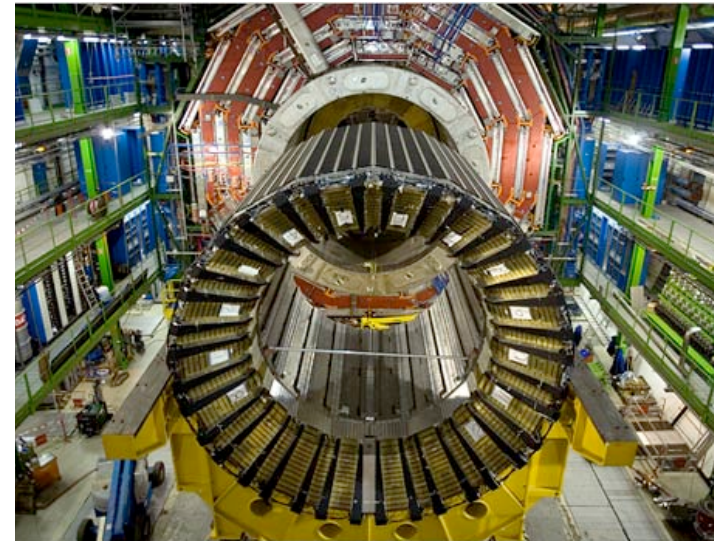
2008

14 TeV proton antiproton collisions in the LEP tunnel

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



Atlas Detector



CMS Detector

The next few years promise to be exciting

- Discover the Higgs
- Find out what happens
at 10^{-17} cm

Supersymmetry

Extra Dimensions

Mini Black Holes

— The Unexpected

- Learn about this tomorrow
- Invite me back in five years to
tell you about this next chapter

