LHC

The Large Hadron Collider

January 28, 2010

Advertised Topic for Today

What is a Collider?

1. Quick overview of the LHCollider for context
2. Some historical background of the physics that made colliders necessary
3. The US legacy in physics and colliders

Part 1

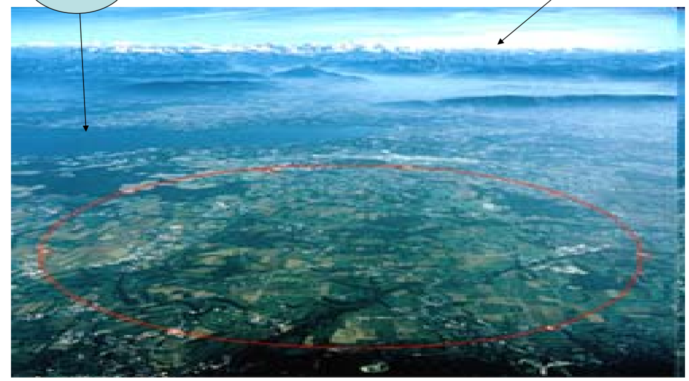
For context:

A Very Quick Overview of the LHC

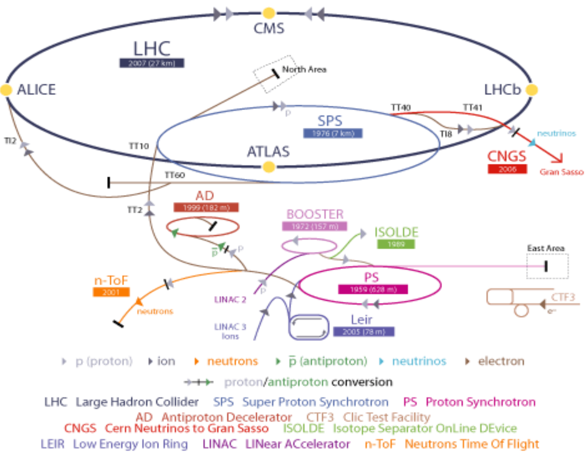
L

THE LHC

Why?



On a clear day . . .



Prefixes and Names for Large and Small Numbers

Metric Prefix	Metric Symbol	Common Name (American and modern British "short scale")	Decimal Equivalent	Exponential
		google[1]		10^{100}
yotta	Y	septillion	1,000,000,000,000,000,000,000,000	10^{24}
zetta	Z	sextillion	1,000,000,000,000,000,000,000	10^{21}
exa	E	quintillion	1,000,000,000,000,000,000	10^{18}
peta	P	quadrillion	1,000,000,000,000,000	10^{15}
tera	T	trillion	1,000,000,000,000	10^{12}
giga	G	billion	1,000,000,000	10^{9}
mega	M	million	1,000,000	10^{6}
kilo	k	thousand	1,000	10^{3}
hecto	h	hundred	100	10^{2}
deca	da	ten	10	10^{1}
no prefix		one	1	10^{0}
deci	d	tenth	0.1	10^{-1}
centi	c	hundredth	0.01	10^{-2}
milli	m	thousandth	0.001	10^{-3}
micro	μ	millionth	0.000001	10^{-6}
nano	n	billionth	0.000000001	10^{-9}
pico	p	trillionth	0.000000000001	10^{-12}
femto	f	quadrillionth	0.000000000000001	10^{-15}
atto	a	quintillionth	0.000000000000000001	10^{-18}
zepto	z	sextillionth	0.000000000000000000001	10^{-21}
yocto	y	septillionth	0.000000000000000000000001	10^{-24}

[1] Invented more for fun than for use, the googol lies outside the regular naming systems.

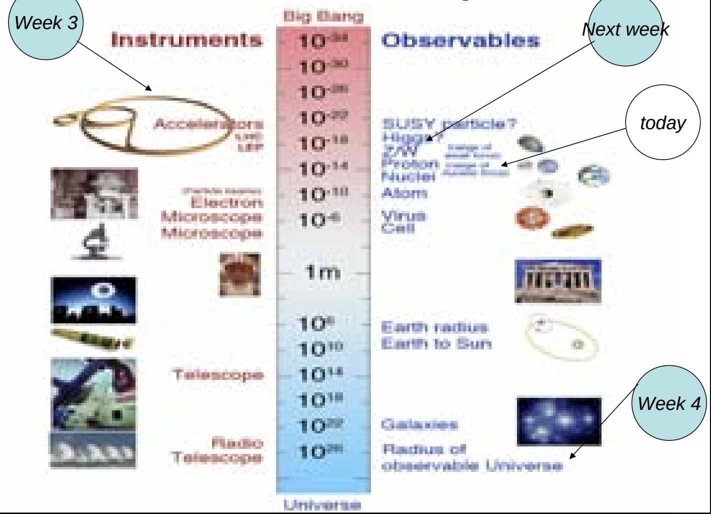
Every day Scales/Measures

- Trillion – a 1,000 billion (10^{12})– US Debt: *terabucks*
- Billion – a 1,000 million (10^{9})– Bill Gates fortune, the population of China, 3 Billion is number of ATCG rungs in human DNA, Hard Drive storage *Gigabytes*
- Million – a 1,000 thousand (10^{6})– Cost of a home in Fairfax County, ~300 million is population of US *Megabytes*

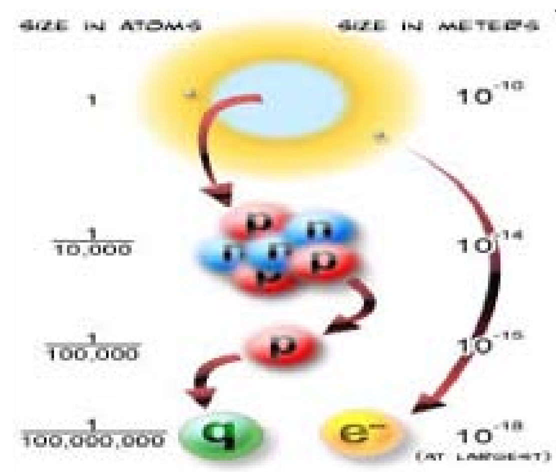
Small scales

- 1 meter – you and me
- 1/1000 (10^{-3}) – diameter of human hair and ~limit of what human eye can see clearly *mille*
- 1/10,000 m – size of a cell
- 1/1,000,000 (10^{-6}) m –bacteria, wavelength of visible light, *micron*
- 1/100,000,000 (10^{-9}) m – size of atom is ten nanometers; flash drives are iPod Nanos; *Nano*
- 10^{-10} m = 1 Angstrom, used for size of atom, 4000-7000A is visible light

The Size of Things



I am the very model of a modern major atom



Part 2. Some historical background
The Physics rationale for colliders

imagination

required

On the Shoulder of Giants: ***Some Historical Perspective***:
The Driving Questions of Pre-modern Physics: *How does the solar system work? What is the nature of light?*

- 1543 – Copernicus publishes *De Revolutionibus Orbium Coelestium*
- 1686 Newton completes *Principia Mathematica*
- 1801 Young's double slit experiment shows that light is a wave
- 1860 Maxwell completes his equations
- 1887 The Michelson Morley experiment fails to detect the ether
- 1897 J.J. Thomson discovers the electron (NPP06)

On the Shoulder of Giants: *Historical Perspective*

The Driving Question of Modern Physics: How does the atom work?

- *1900 Planck resolves ultraviolet catastrophe (NPP18)*
- *1905 Einstein explains the photoelectric effect (NPP21)*
- *1911 Rutherford discovers his atomic nucleus (NPC08)*
- *1913 Bohr publishes his quantum theory of the atom (NPP21)*
- 1916 Einstein publishes General Theory of Relativity
- 1923 DeBroglie sets forth matter-wave hypothesis (NPP29)
- 1927 Heisenburg states his uncertainty principle (NPP32)
- 1930 Dirac, Schrödinger develop wave mechanics (NPP1933)
- 1932 Anderson discovers positron (NPP36)
- 1939 Lise Meitner identifies nuclear fission

Topics for today

On the Shoulder of Giants: *Historical Perspective*

The Driving Question of Modern Physics: How does the atom work?

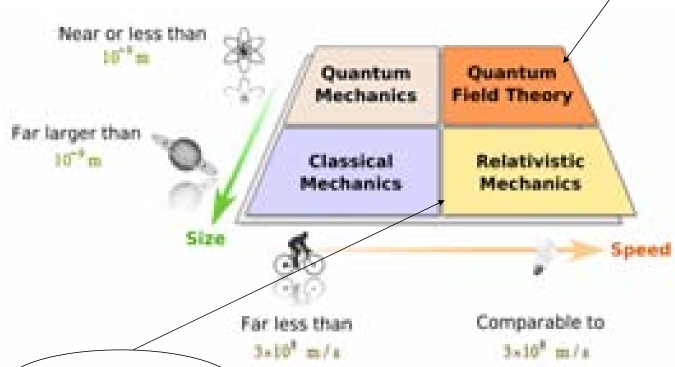
- 1948 Feynman, Tomonaga & Schwinger combine QM and Special Relativity in Quantum Electrodynamics or QED (NPP65)
- 1964 Quarks proposed as fundamental (Gell-Mann NP69)
- 1983 Experimental verification of QED (Rubia, van der Meer, NPP84)
- 1994 Existence of Top Quark confirmed
- 1998 Neutrinos found to have nonzero mass

2009 LHC sets record -- and immediately shuts down for winter

Topics for next week

What about relativity?

LHC's raison d'etre



Michelson, Morley
Einstein on the nature of light

At the end of the 19th century, some real successes

PERIODIC TABLE - BEFORE WORLD WAR II

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
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
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	(43)	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57–71 La–Lu	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)	86 Rn
(87)	88 Ra	89 Ac	90 Th	91 Pa	92 U	(93)	(94)	(95)	(96)	(97)	(98)	(99)	(100)				
		57 La	58 Ce	59 Pr	60 Nd	(61)	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	

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A view at 1900

Lord Kelvin, to the AAAS, 1900:

"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

Classical physics can't explain

1. the existence of atoms
2. the Ultraviolet Catastrophe
3. the Photoelectric Effect
4. the Discreet Spectra of Atoms

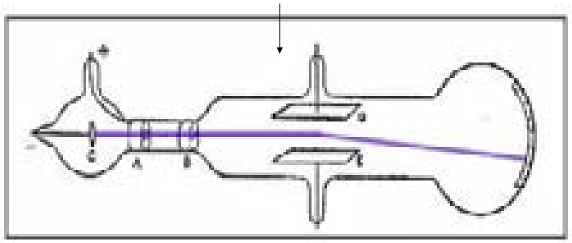
Some historical background of the physics

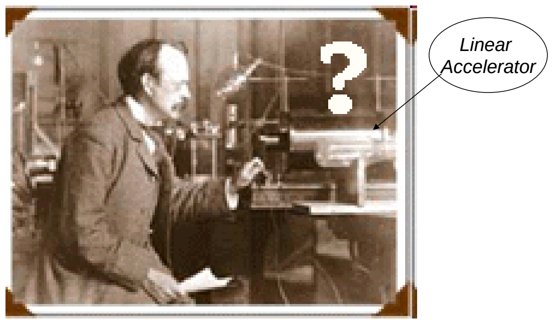
Or, in the Beginning of Modern Physics, Physicists asked:

"How does the atom work?"

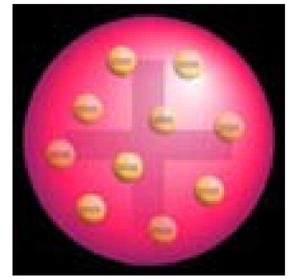
Thomson discovers electron

(linear accelerator)

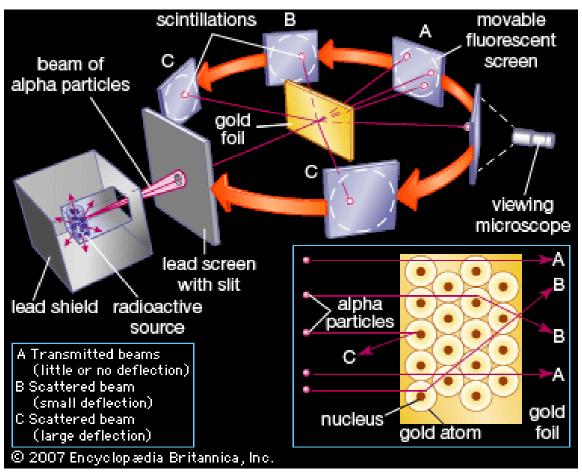




Thomson's view of the atom



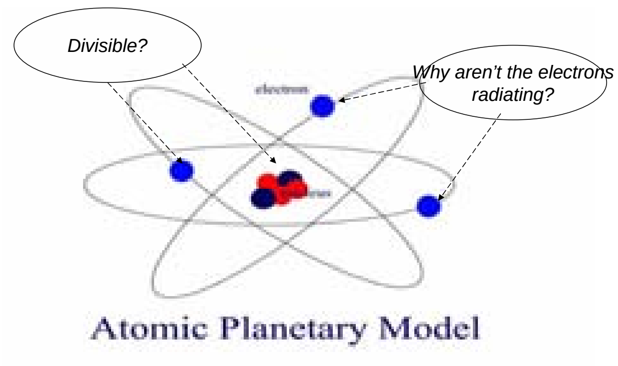
The 1910 version of a collider



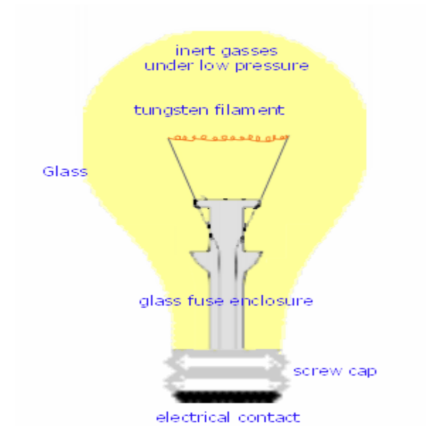
Rutherford's experiment

Animation

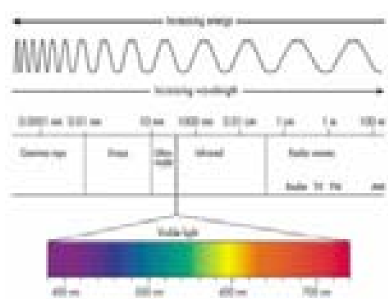
1910-1911 Rutherford's Model



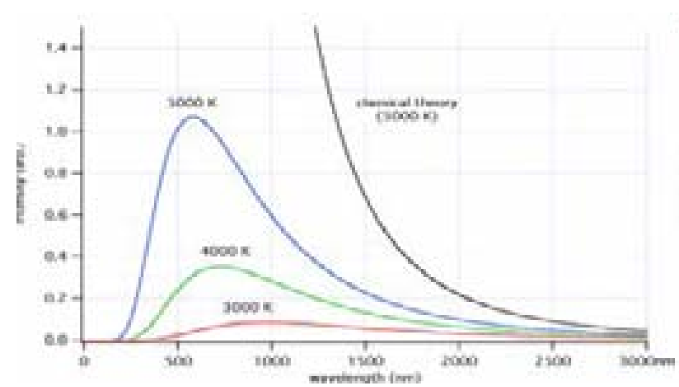
The Ultraviolet Catastrophe



The ultraviolet catastrophe: Why not blue hot?



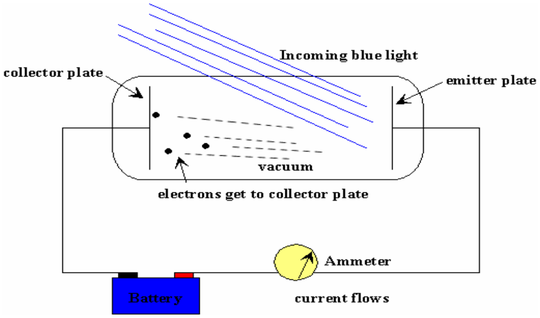
Ultraviolet catastrophe: why less light at higer energies/lower wavelength?



Planck's solution: a "fudge factor"

- *E = hf or E = hv (E = n hv)*
- *Planck's constant = 6.626068 × 10^{-34} m^2 kg / s*
- *= 6.582 x 10^{-25} GeV second*

1905: Einstein solves the photoelectric puzzle



Photoelectric Effect: Classical physics could not explain

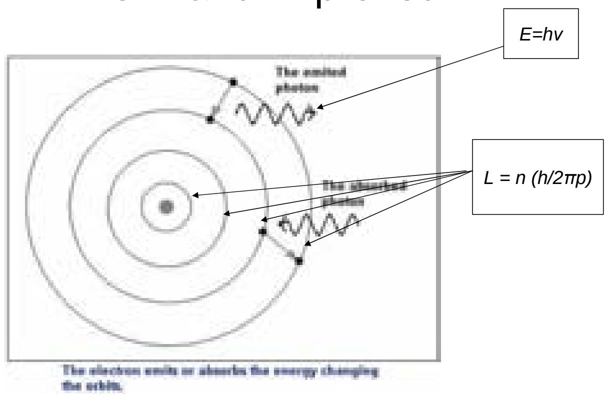
1. The electrons were emitted immediately.
2. Increasing the intensity of the light increased the number of photoelectrons, but not their maximum kinetic energy
3. Red light will not cause the ejection of electrons, no matter what the intensity.
4. A weak violet light will eject only a few electrons, but their maximum kinetic energies are greater than those for intense light of longer wavelengths

Photoelectric effect

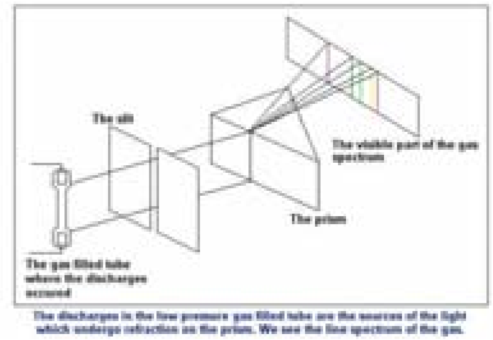
$K.E._{max} = h(v - v_0) = hv - \Phi$

Where Φ is the work function, the energy needed for an electron to escape from the metal

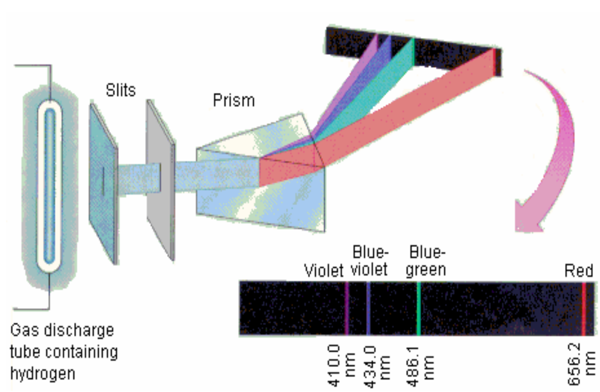
1913: The Bohr Model of the Atom: New! and Improved!



And solves a problem



$$\frac{1}{\lambda_{\mathrm{vac}}} = R_{\mathrm{H}} \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right).$$



Another Approach

DeBroglie asked, if light waves can be particles, can particles be waves?

.

deBroglie's insight: properties or particles and wave are equivalent

Particles' properties

Energy: $E = mc^2$

momentum p given by mv

$E = pc$

Waves properties

Energy is $E = h\nu$ where ν is frequency

Since $c = \nu \lambda$ where λ is wavelength

Since $E = h\nu = pc$, then $pc = h (c/ \lambda)$

$p\underline{c} = h (\underline{c}/ \lambda)$

$$\mathbf{p = h/ \lambda}$$

So What?

Debroglie's Ideas explained why electrons could only stay in certain orbits in Bohr's theory of the atom!

If electrons are waves orbiting a nucleus, they have to be whole waves :

$2\pi r = n\lambda$

So that the wave re-enforces constructively itself in each orbit

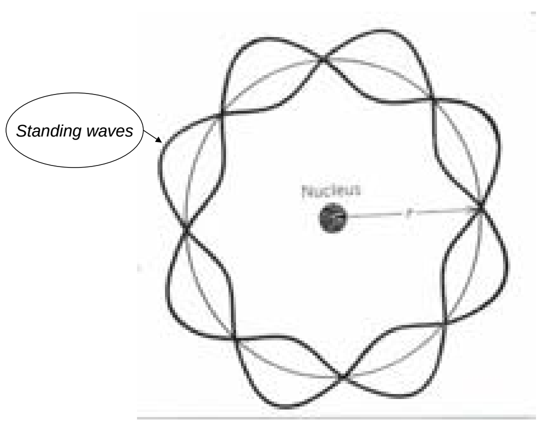
$2\pi r = nh/p = nh/mv$

mvr (angular momentum) = $pr = nh/ 2\pi$; $mvr = L$, so

$L = n (h/ 2\pi)$

And this explains Bohr's model of the atom, where electrons have orbits defined by their angular momentum!

Electrons as waves orbiting a nucleus have to be whole waves :



1927: Heisenberg's uncertainty principle

Gives limit on how much we can know by:

$$\Delta p \Delta x \sim h/2\pi$$

i.e.

$$m \Delta v \Delta x \sim h/2\pi$$

OR

$$\Delta E \Delta t \sim h/2\pi$$

Schrödinger

Solving Schrödinger's equation, based on wave mechanics, produces the periodic table!

To understand the weirdness of Quantum Mechanics

http://research.microsoft.com/apps/tools/tuva/

These are B&W videos of the famous Messenger Lectures on the Character of Physical Law given by Richard Feynman at Cornell in 1964

to a general, college (e.g. OLLI) audience

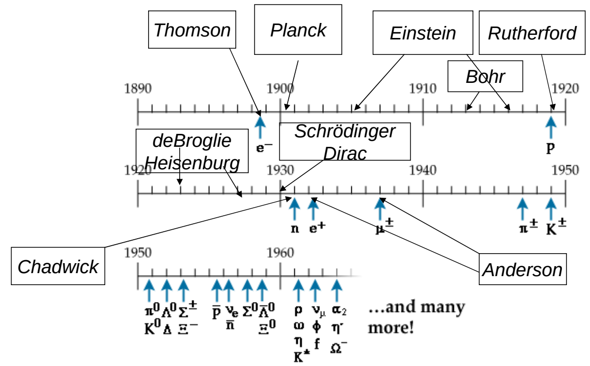
Go to Lecture 6, Probability & Uncertainty

Richard Feynman:

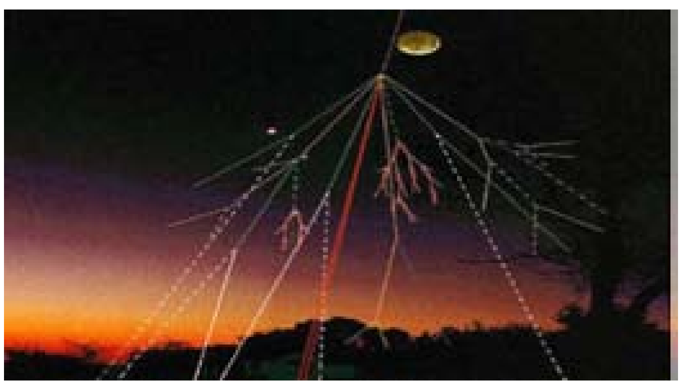
“ . . .I think I can safely say that nobody understands Quantum Mechanics.”

p. 129,Tthe Character of Physical Law, 1986, MIT Press, 13th Printing

Where are we?



Discovery of the muon

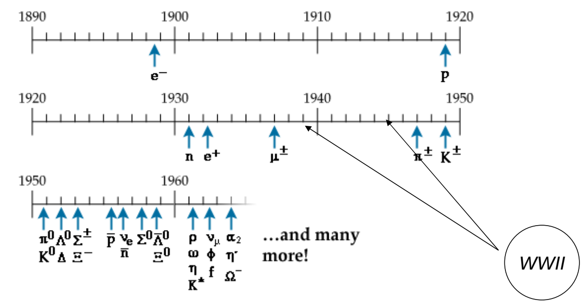


1935: Yukawa

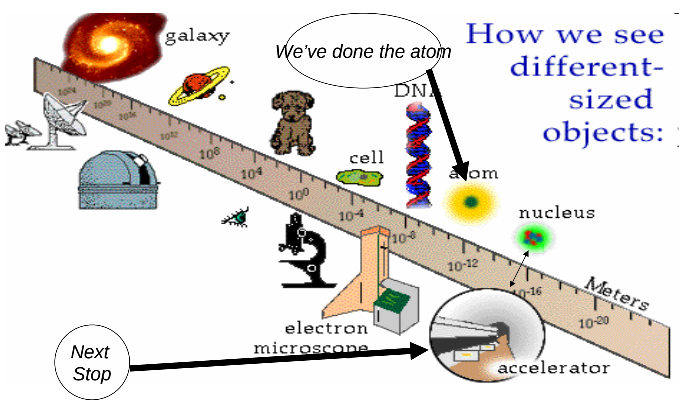
- A new view of force: an exchange of particles between nucleons
- Animation - particle force carrier

End of WWII: Where are we?

The particle floodgates open after WWII



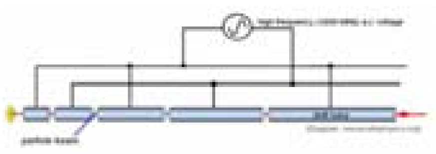
Where are we?



Part 3. The US legacy in colliders (and physics)

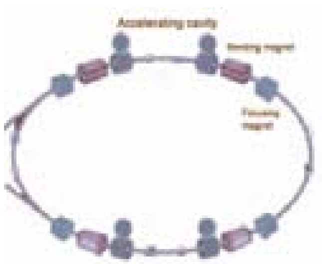
- Lawrence Radiation Laboratory
  ➔Lawrence Berkeley National Laboratory
- Brookhaven National Laboratory
- Stanford Linear Accelerator Center
- Fermi National Accelerator Laboratory

Linear accelerators

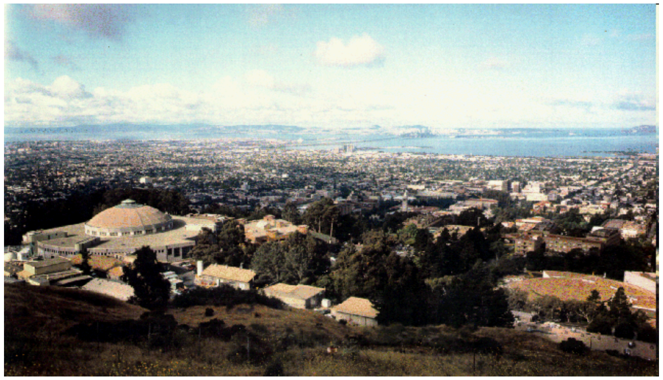


Types of Particle Accelerators

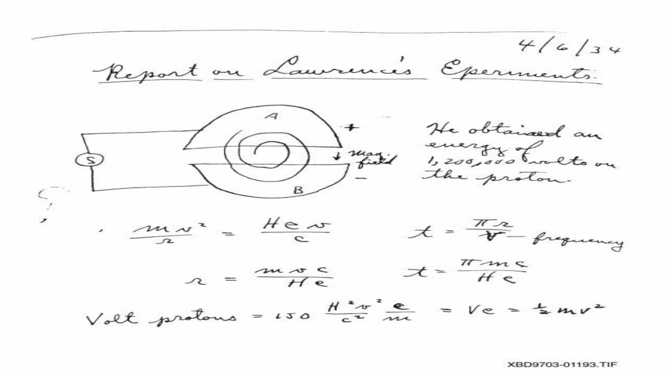
Circular accelerators



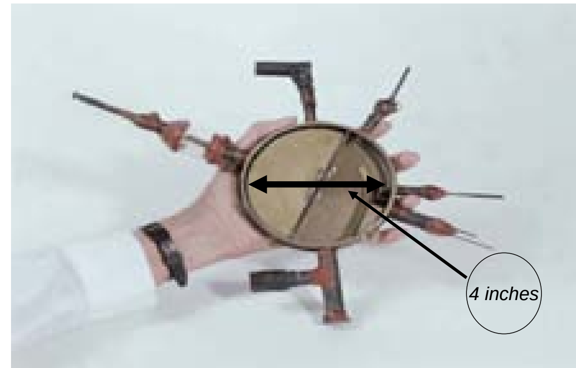
Lawrence Radiation Lab
~ 1937:



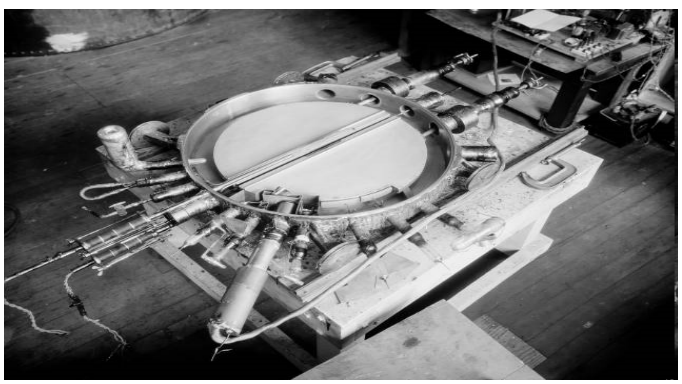
How a cyclotron operates



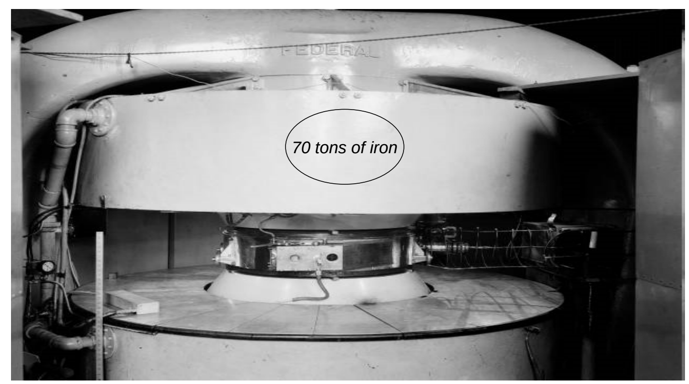
The first cyclotron, 1931, 7 keV



27-inch cyclotron, ~1932; 6 MeV deuterons



37 inch cyclotron ~1938, 8 MeV deuterons



60 inch cyclotron
~1939, 16 MeV deuterons

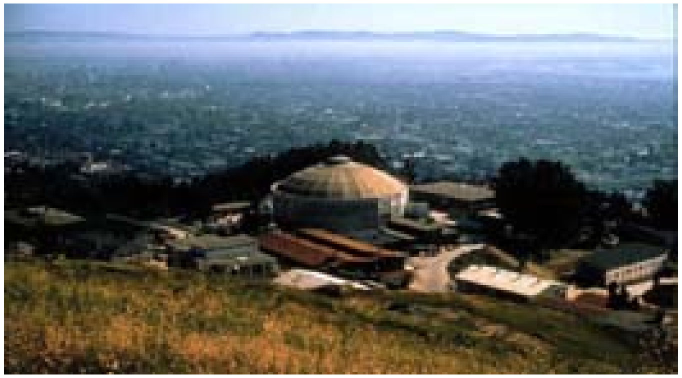
200 ton magnet

60” cyclotron, 1939

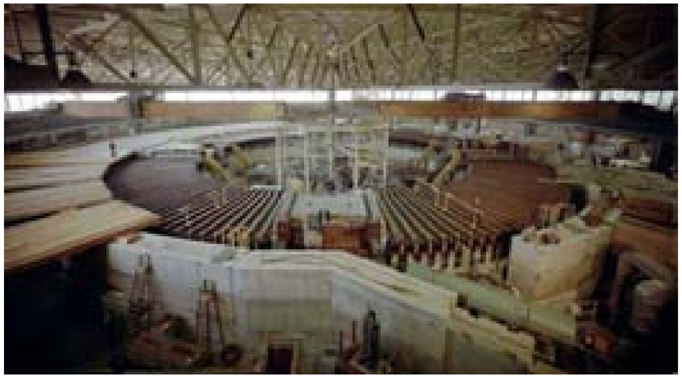
184 inch cyclotron, ~1946

Lawrence and the staff shown with the 184-inch magnet. *(Lawrence Radiation Laboratory)*

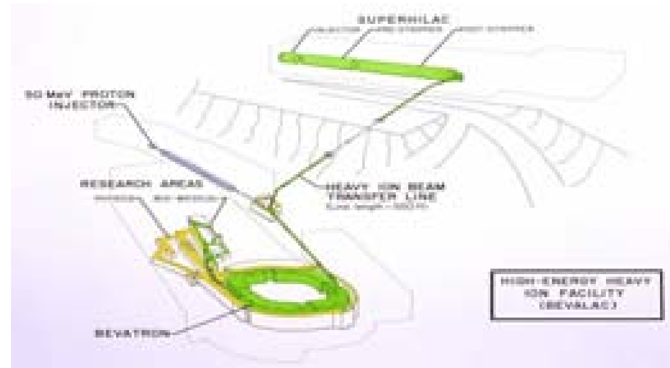
Housing of the 184” cyclotron



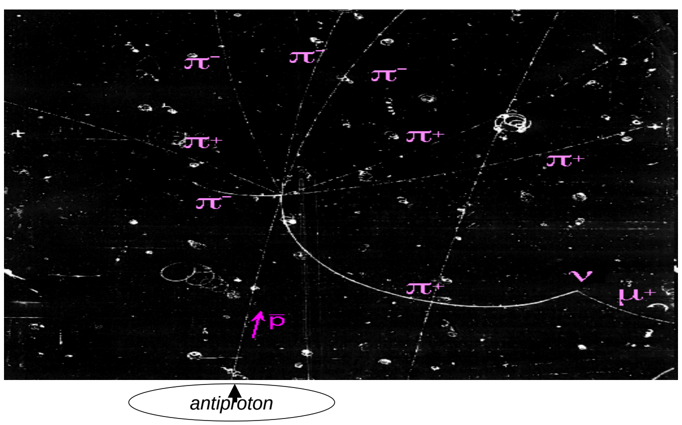
The Bevatron
1954, 6 BeV protons



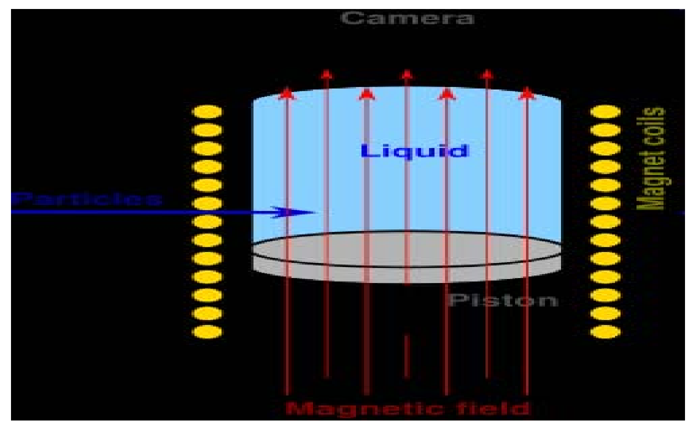
The Bevalac, ~1974



Bubble Chamber



Bubble chamber



Making history at LBNL

The Chemical Properties of Elements 94 and 93

by Glenn T. Seaborg and Arthur C. Wahl

Journal of the American Chemical Society **70**, 1128 (1948).
(Submitted as a secret report on March 21, 1942.)

"Plutonium is suggested as the name for element 94 following the convention that was used in the naming of neptunium (element 93) and uranium. The chemical symbols Pu and Np are suggested for plutonium and neptunium."

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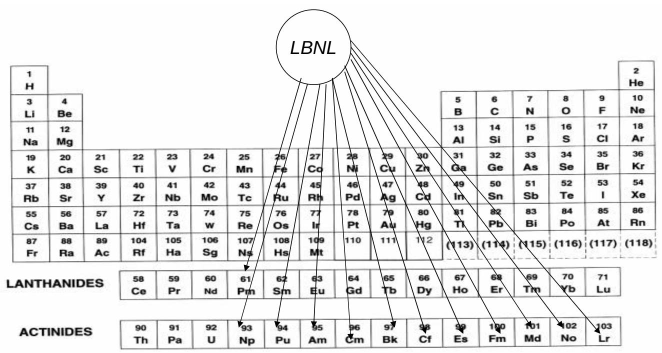
Results of research

CHEMICAL ELEMENTS DISCOVERED AT BERKELEY

43	technetium*
85	astatine
93	neptunium
94	plutonium
95	americium**
96	curium**
97	berkelium
98	californium
99	einsteinium
100	fermium
101	mendelevium
102	nobelium
103	lawrencium
104	rutherfordium
105	hahnium
106	seaborgium

* Discovered in Italy using sample from Berkeley cyclotron bombardment
** Discovered in Chicago by Berkeley team

Modern Periodic Table



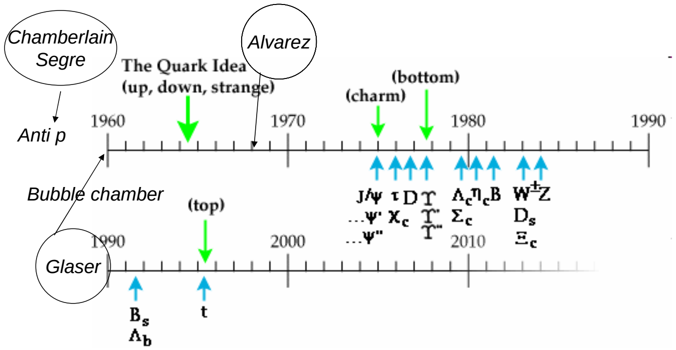
Spin offs

Radioisotopes Discovered at LBL Commonly Used in Nuclear Medicine

27/37-Inch Cyclotron		60-Inch	184-Inch
Oxygen-15	Gallium-67	Hydrogen-3	Magnesium-28
Fluorine-18	Rubidium-86	Carbon-14	Iron-52*
Calcium-45	Molybdenum-99*	Magnesium-28	Copper-67
Chromium-51	Technetium-99m*	Potassium-43	Zinc-62
Manganese-52*	Tin-113	Rubidium-81	Germanium-68
Manganese-54*	Iodine-124*	Iodine-123	Rubidium-81
Iron-59*	Iodine-130*	Mercury-197	Rubidium-82
Cobalt-57*	Iodine-131*		Strontium-82
Cobalt-58*	Iodine-132		Cesium-129
Cobalt-60*	Xenon-133		Thallium-201

*Glenn T. Seaborg involved in discovery

And the result of the investment is:

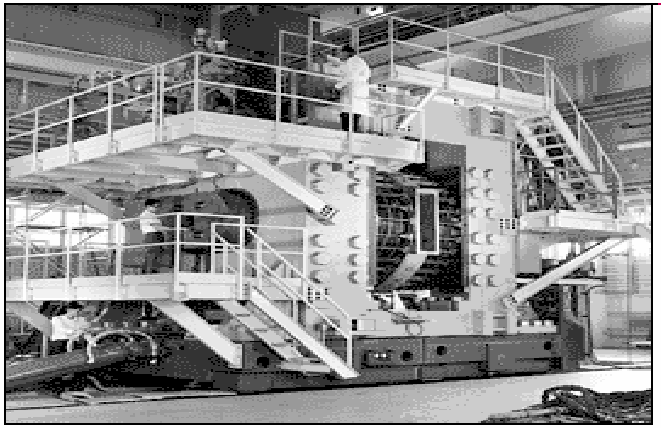


Brookhaven National Laboratory

BNL Cosmotron, 1953

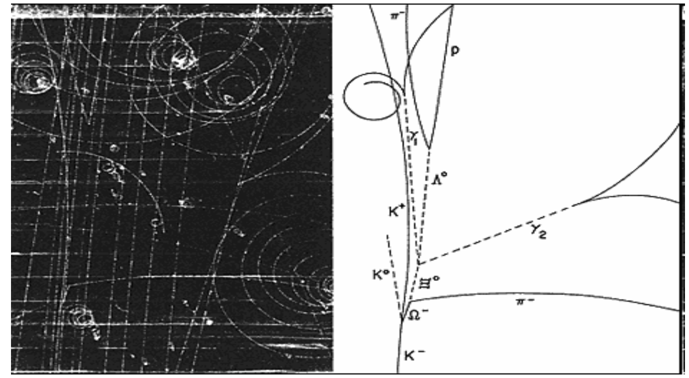
AGS ~ 1960

A “microscope” for subatomic particles:

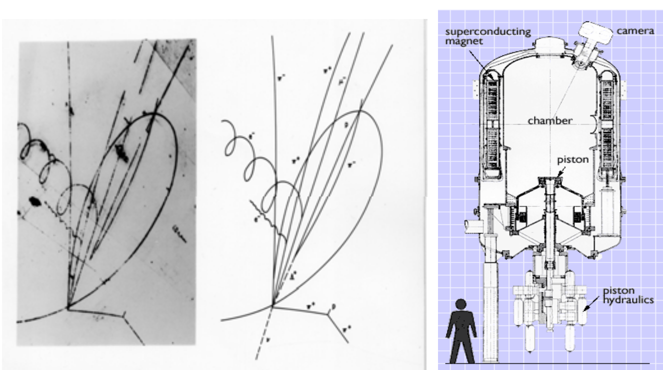


The 80-inch Bubble Chamber

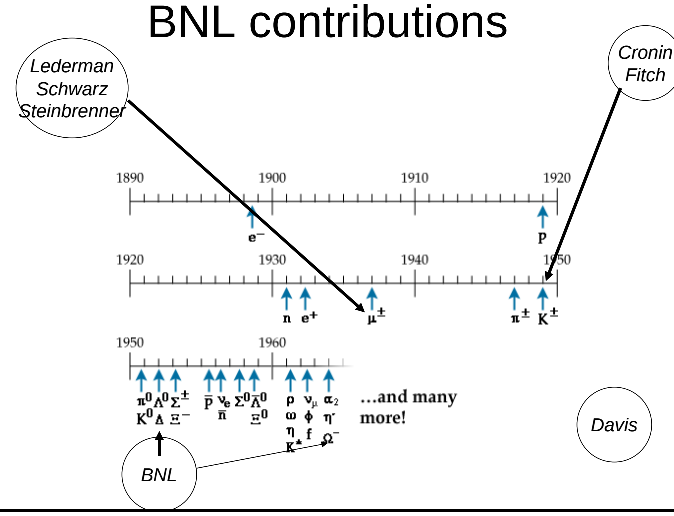
A famous result from the AGS and the 80” Bubble Chamber:



Another BNL discovery: charm quarks



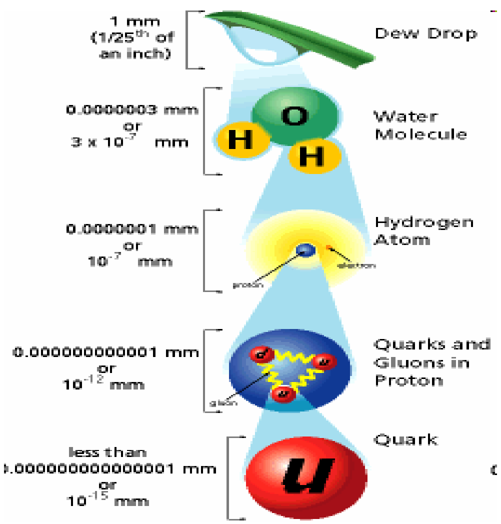
BNL contributions



A Brief History of SLAC

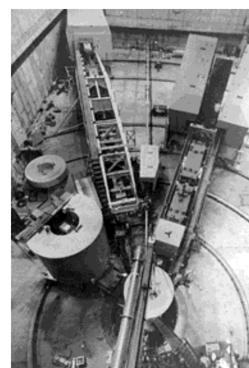
The First 47.5 Years: 1962 to 6.2009

1960s…



1990s

Friedman, Kendall, Taylor Nobel Prize



1970s …

SPEAR
under
construction

1970s …

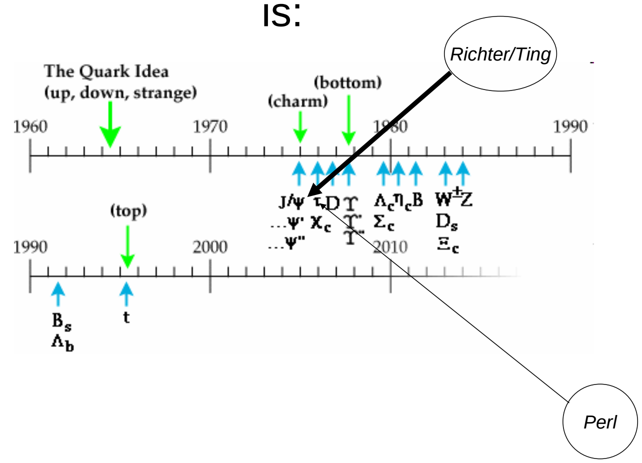
November
Revolution 11/11/1974

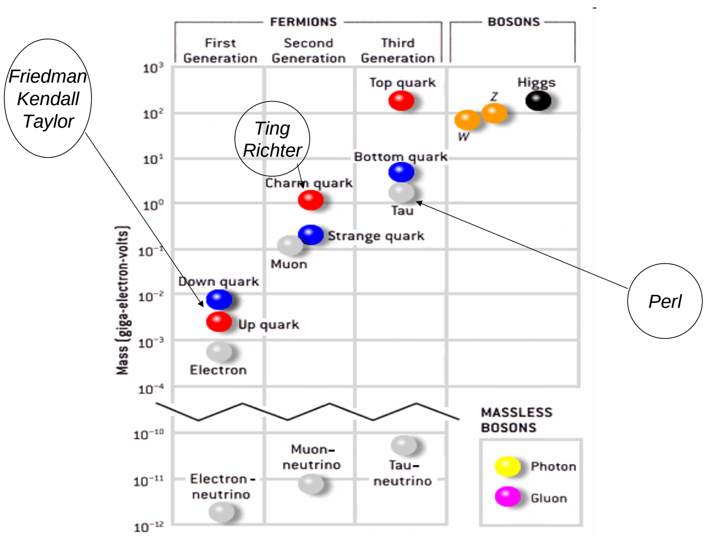
Burton Richter and Sam Ting shared Nobel Prize in Physics, 1976

1970s …

- Martin Perl at 1995 Nobel Prize press conference at SLAC

And the result of the investments is:



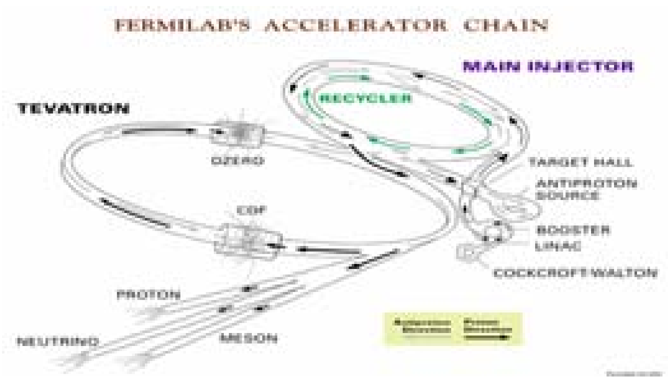


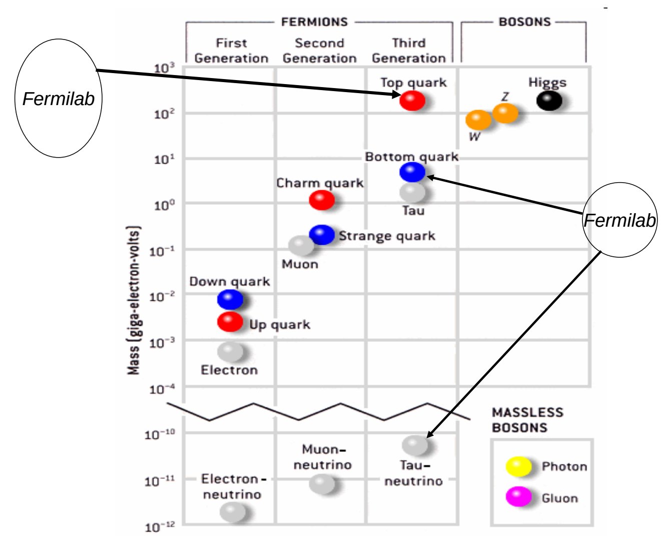
Whither Stanford today?

Fermi National Accelerator Laboratory (Fermilab)

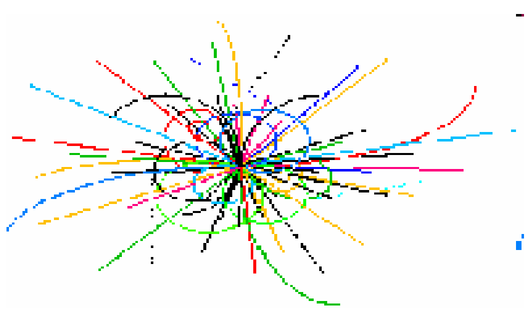
The Tevatron

Tevatron Schematic





The SSC



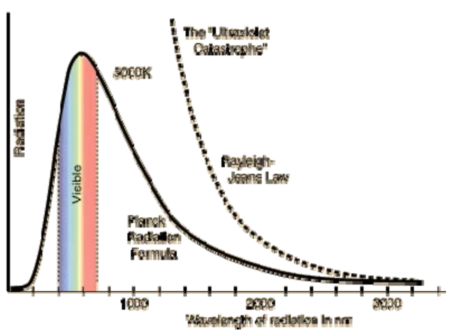
SSC

LHC – the SSC fall back

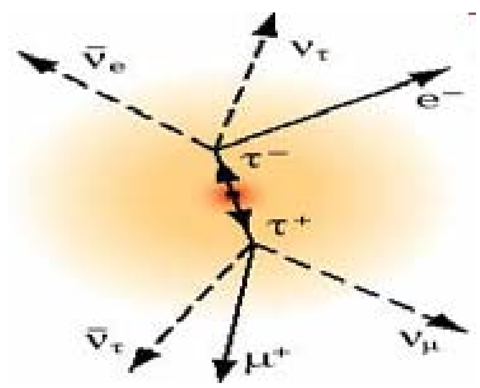
- The LHC is hip!

BACKUP

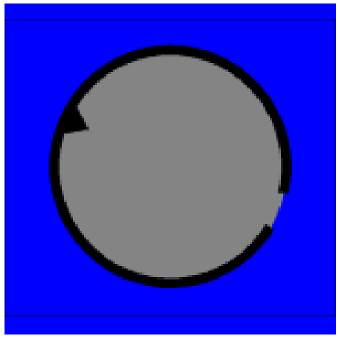
The ultraviolet catastophe



Discovery of the tau



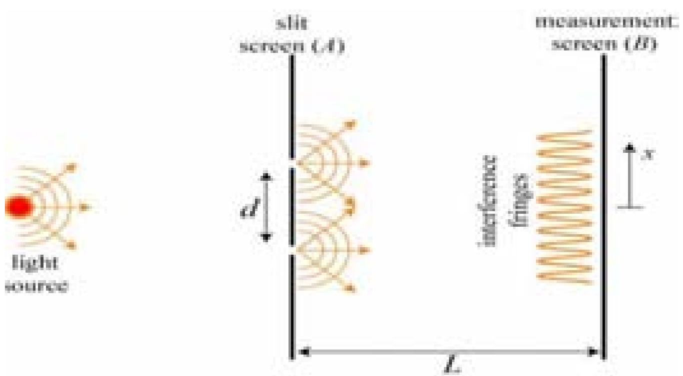
The Ultraviolet Catastrophe Blackbody Radiation



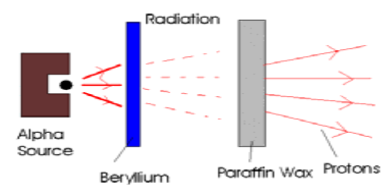
The experiment to understand QM (C/o Max Born)

Electrons sent one at a time through 2 slits will produce points on a screen, but eventually produce an interference pattern, as if they were waves!

Young's experiment had proved light is a wave

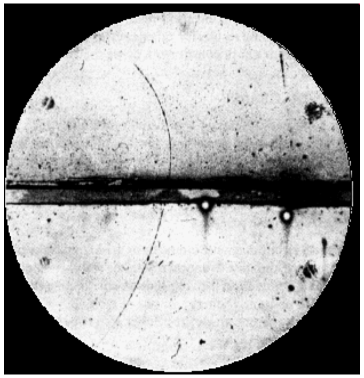


Discovery of the neutron

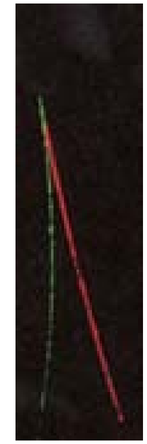


$${}^{9}_{4}Be \quad {}^{4}_{2}He \rightarrow {}^{12}_{6}C \quad {}^{1}_{0}n$$

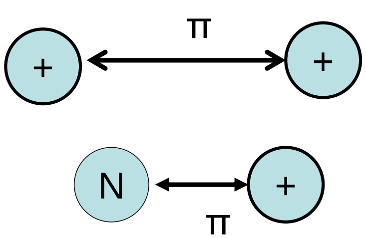
Discovery of the Positron (e^+)



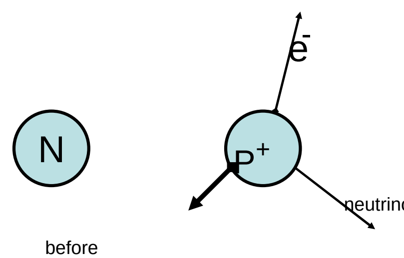
Why is the more matter than antimatter?



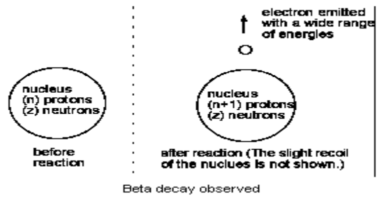
Strong force



Radioactivity: Beta decay, discovery of the neutrino

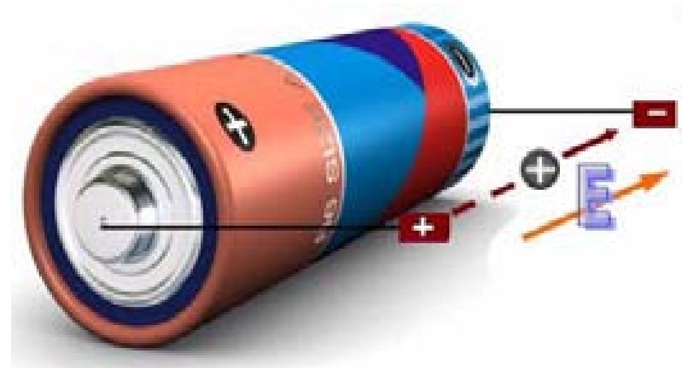


The Neutrino



Neutrino Properties	
Mass	Zero or very small
Speed	The speed of light or slightly less
Charge	Zero
Energy	A continuous range of energies
Varieties	Three types of neutrinos, each with an antiparticle

Mass is measured as Energy!



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

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–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

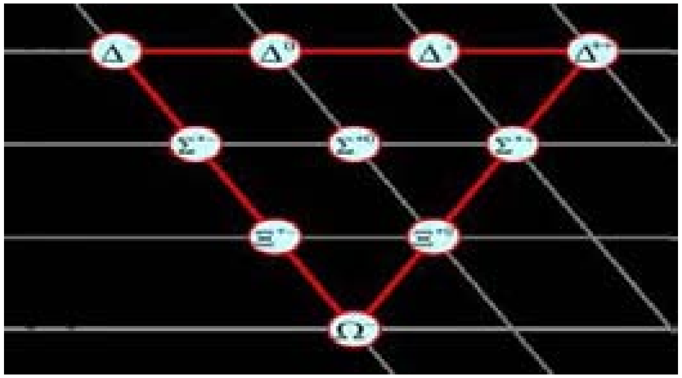
Mesons $q\bar{q}$

Mesons are bosonic hadrons

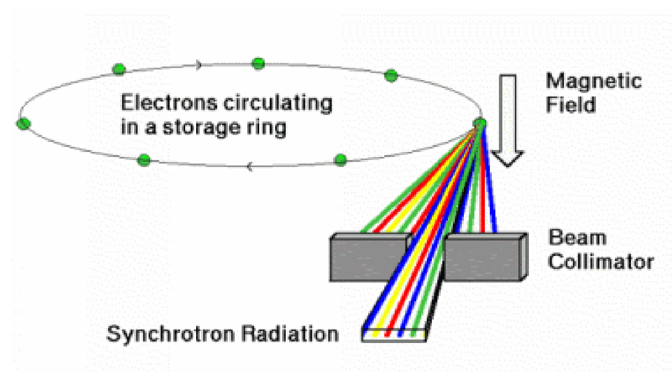
These are a few of the many types of mesons.

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	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

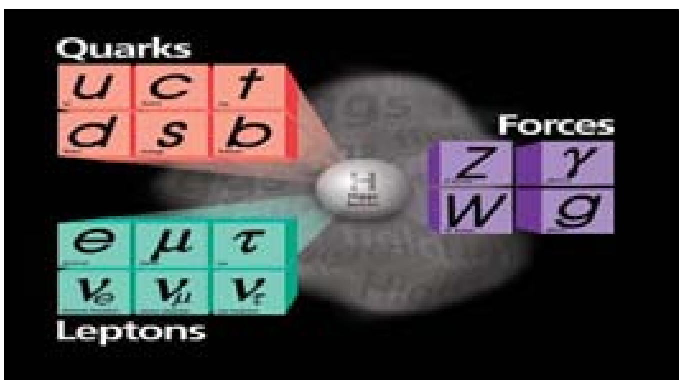
Particles in the Particle Zoo



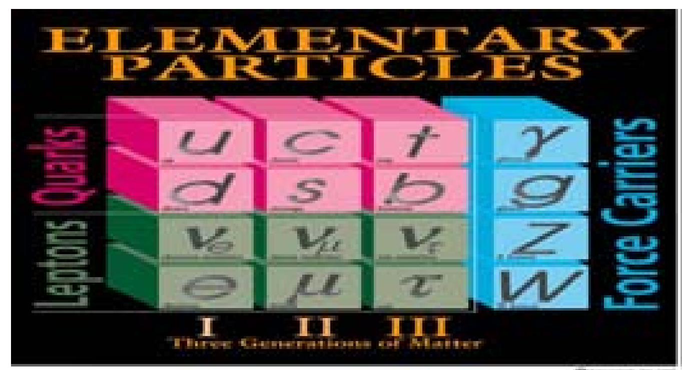
Synchrotron Radiation

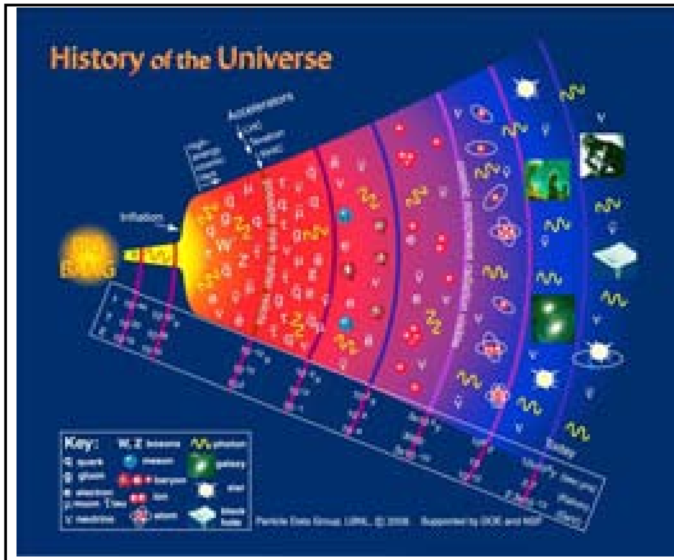


Historic discoveries

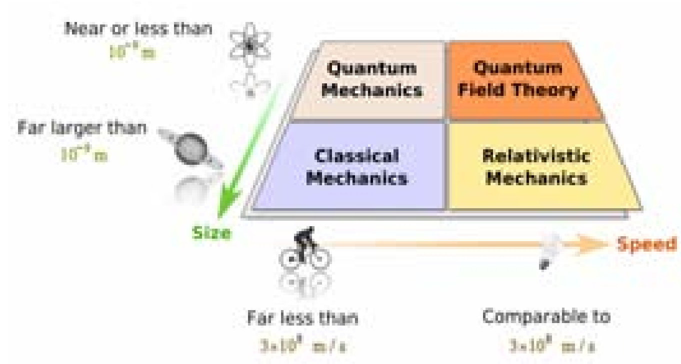


Historic Discoveries

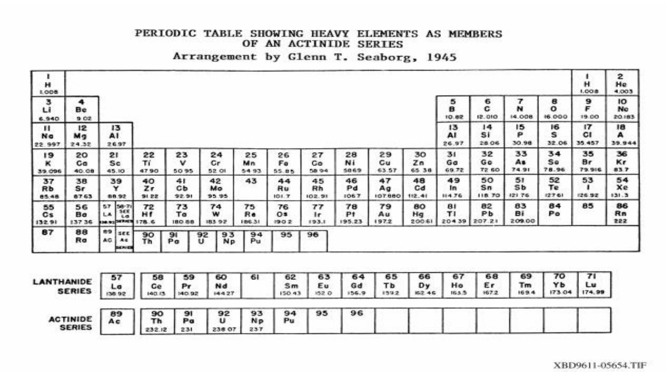




What about relativity?



And an expansion of the Periodic Table



Unsure about the Implications of the Uncertainty Principle?