Introduction into Particle Physics

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FNAL

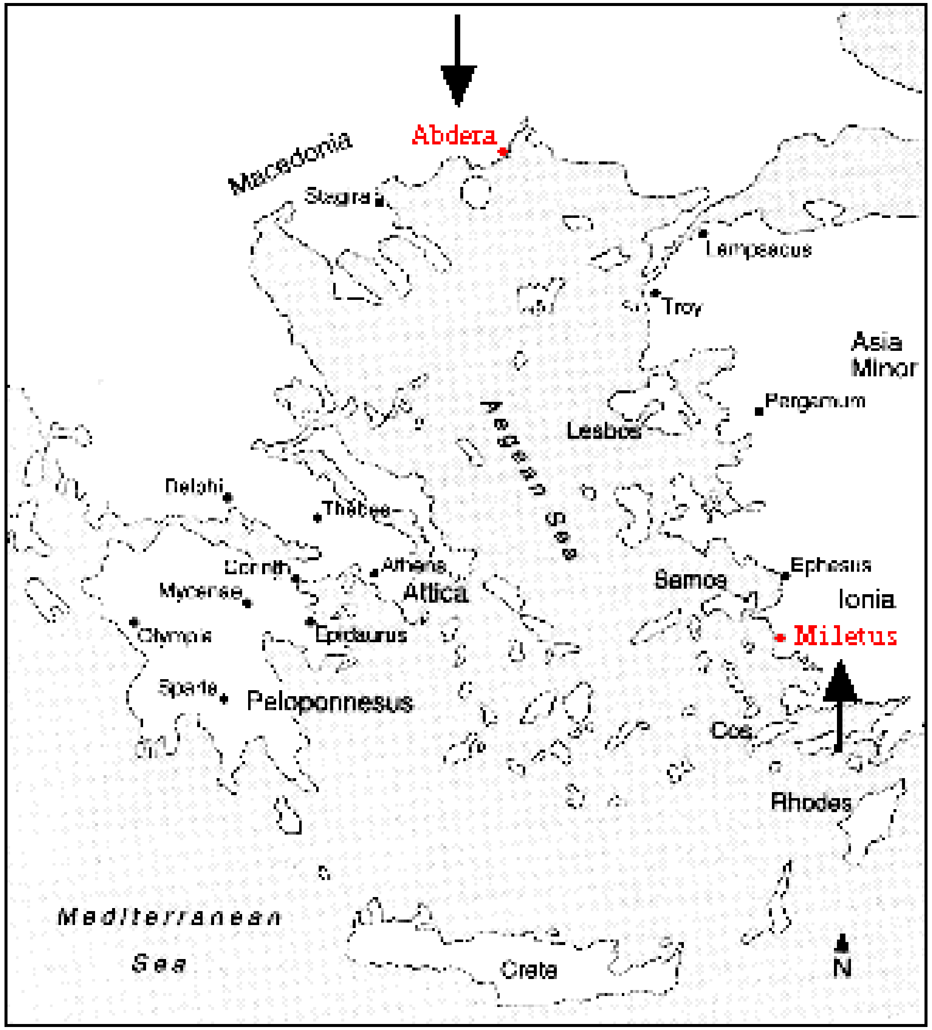
The history of Particle Physics

- Particle physics is the study of the most fundamental structure of matter.
- It has had a long history:
  - 600BC: Greeks, atom
  - 1000-1500: Alchemists, elements
  - 1800's: Atoms revisited
  - Early 1900's: structure of nucleus
  - Mid 1900's: mesons/muons/neutrinos/ …
  - Late 1900's: quarks/intermediate bosons
  - Now: What next?

Greek Atomic Theory

- 440 BC, Leucippus of Miletus

  + Democritus of Abdera
- All matter made of atoms
- Atoms not divisible
- Atoms not touching (vacuum between!)
- Atoms completely solid, no internal structure
- Atoms have different size, shape



Next Developments

- Atomic Theory, opposed by Archimedes, largely forgotten until 1800.
- In meantime, understanding of existence of elements (Gold, Silver, Copper, Iron, Lead, Tin, Mercury, Sulfur, Carbon)
- Understanding of “reversibility” (of chemical reactions) (Could repeatedly oxidize and reduce the same material, re-smelt).

Development of New Atomic Theory

- John Dalton, 1803
- Elements were different because their atoms were different
- All atoms for an element were identical
- Chemical compounds were formed by making combinations of atoms of elements, in ratios of small numbers
- Chemical reactions involve rearrangement of the atoms of the compounds

Feynman on Atomic Theory

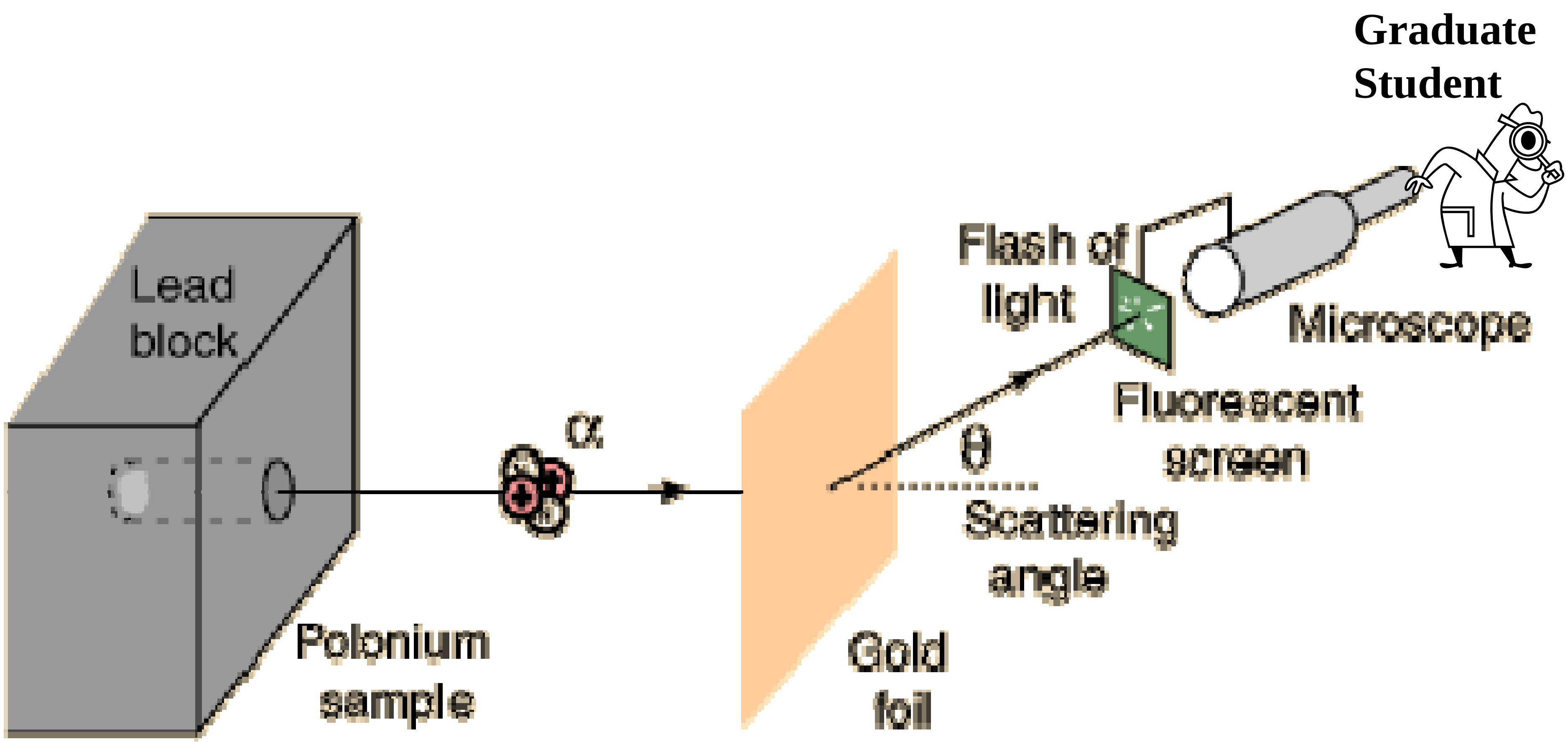
- "If in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the /atomic hypothesis/ (or the atomic /fact/, or whatever you wish to call it) that /all things are made of atoms - little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another/. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied."

  Richard Feynman

Periodic Tables

- First organizations involved periodic properties of the elements (Octaves, John Newland, 1863)
- Then organized by atomic weight (Mendeleev, 1864)
- No organization by atomic number as that was not known

Rutherford Experiment

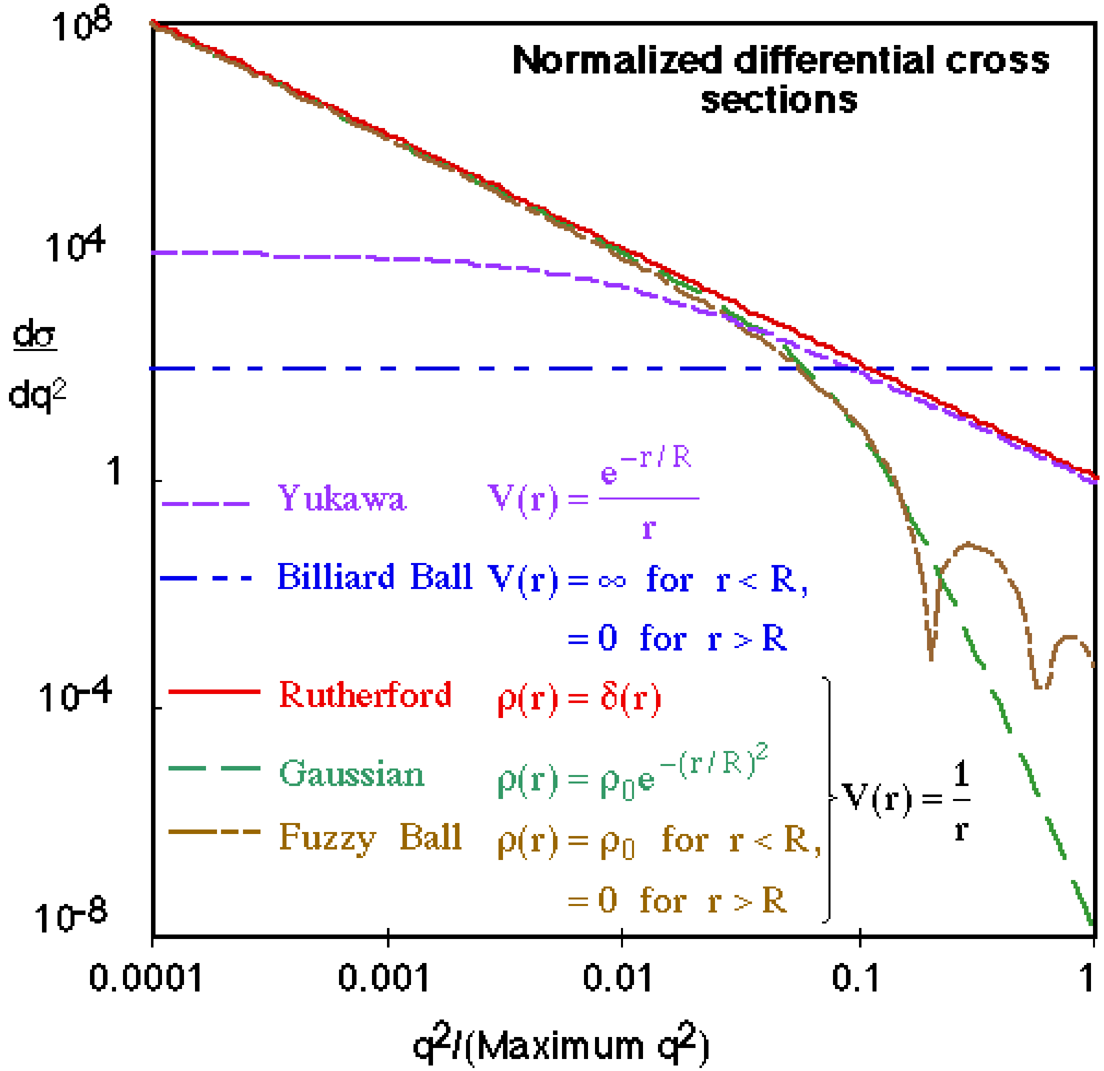


Rutherford and Thompson Scattering

- Link to Scattering
- Rutherford model of atom was a small nucleus where charge was concentrated.
- Experimental results on scattering of alpha particles very different than "plum pudding model of Thompson"
- Rutherford also measured size of nucleus.
- Rutherford Scattering formula (two point particles)

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

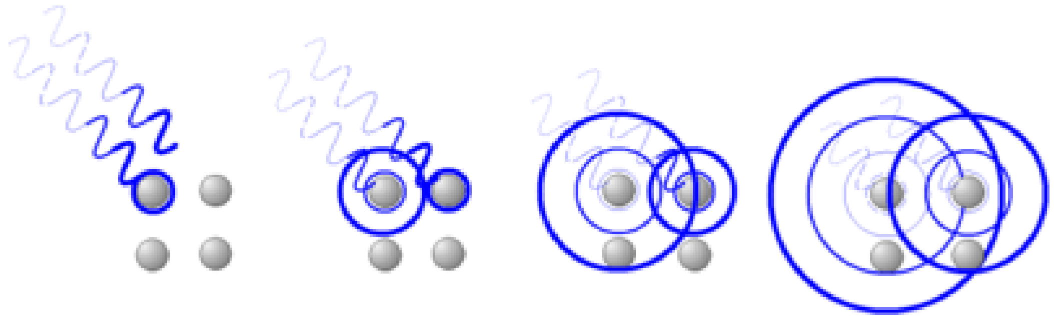
Various Scattering Potentials

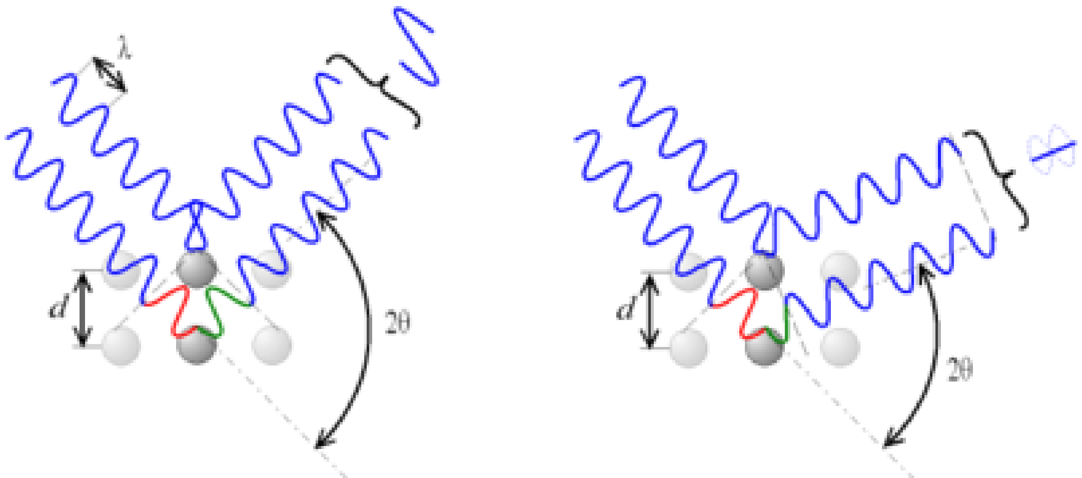


q is momentum transfer

$(q/Q)^2$ proportional to $\sin^2(\theta/2)$

Bragg Scattering

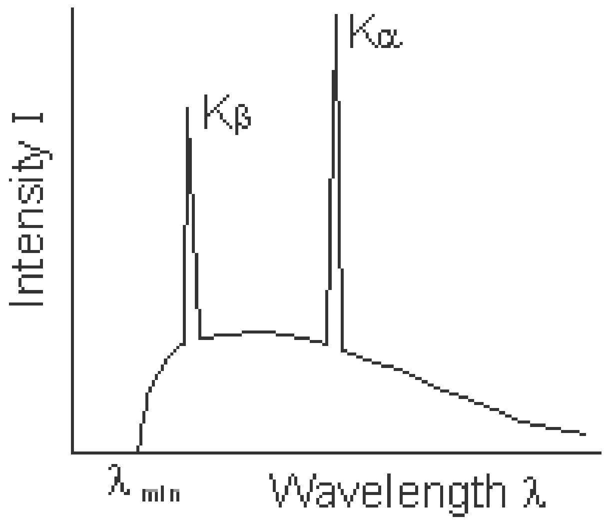




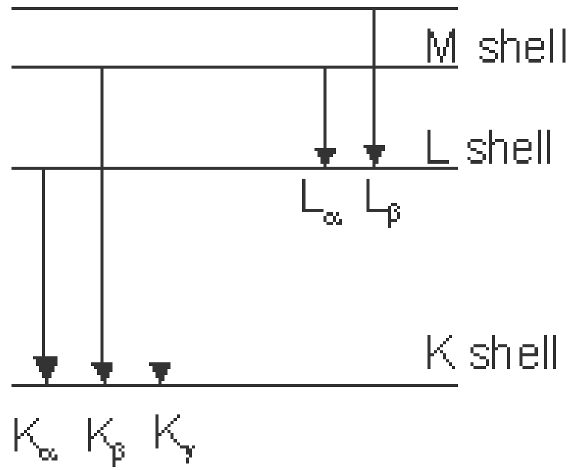
Electric field of x-ray photon accelerates electrons of atom. Electrons emit x-ray of same wavelength Constructive interference of waves emitted by the various atoms of crystal lattice only at discrete angles

$$n\lambda = 2d \sin(\theta)$$

Characteristic X-Ray lines



X ray emission spectrum



Emission of Characteristic X-Ray spectral lines

Atomic electron de-exciting from one level to another emits x-ray with characteristic frequency. K_{α} is line for decay from L to K shell.

Moseley's Experiment

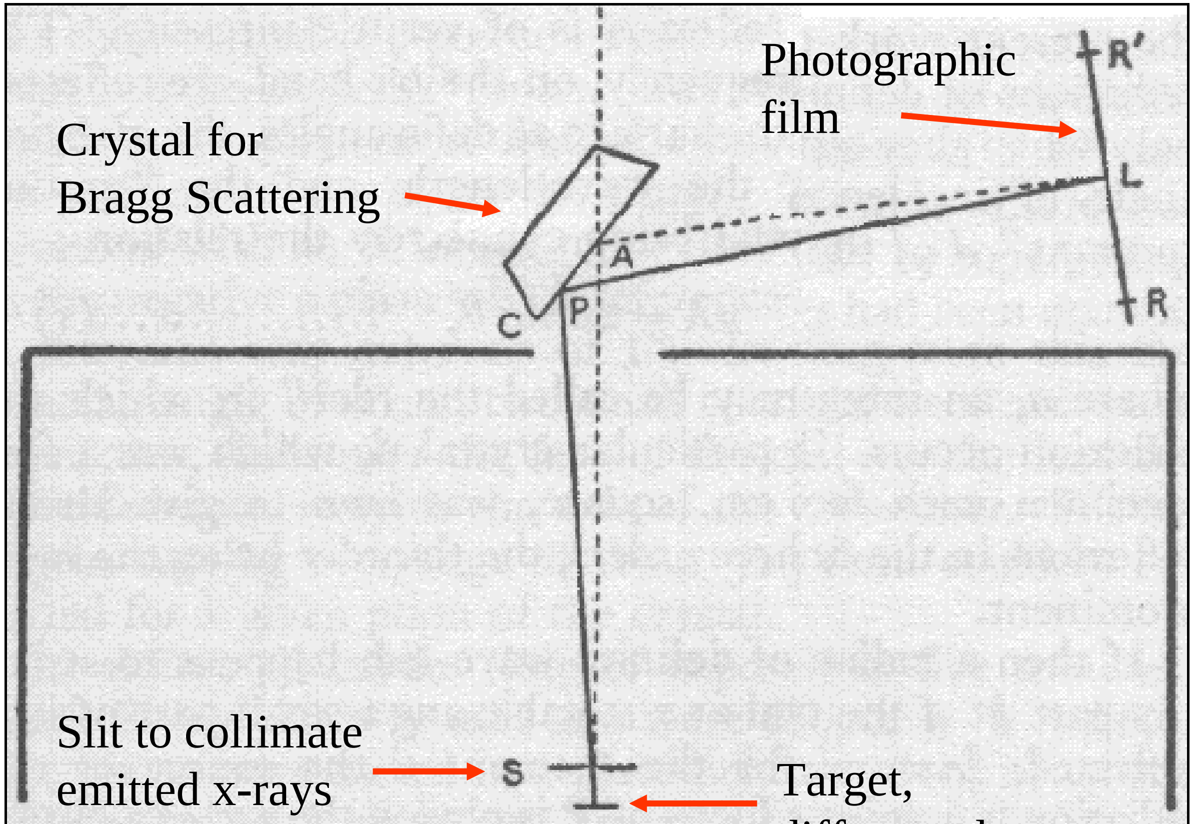


Fig. 1.

Location of "L" depends on wavelength of x-ray

Moseley’s Result

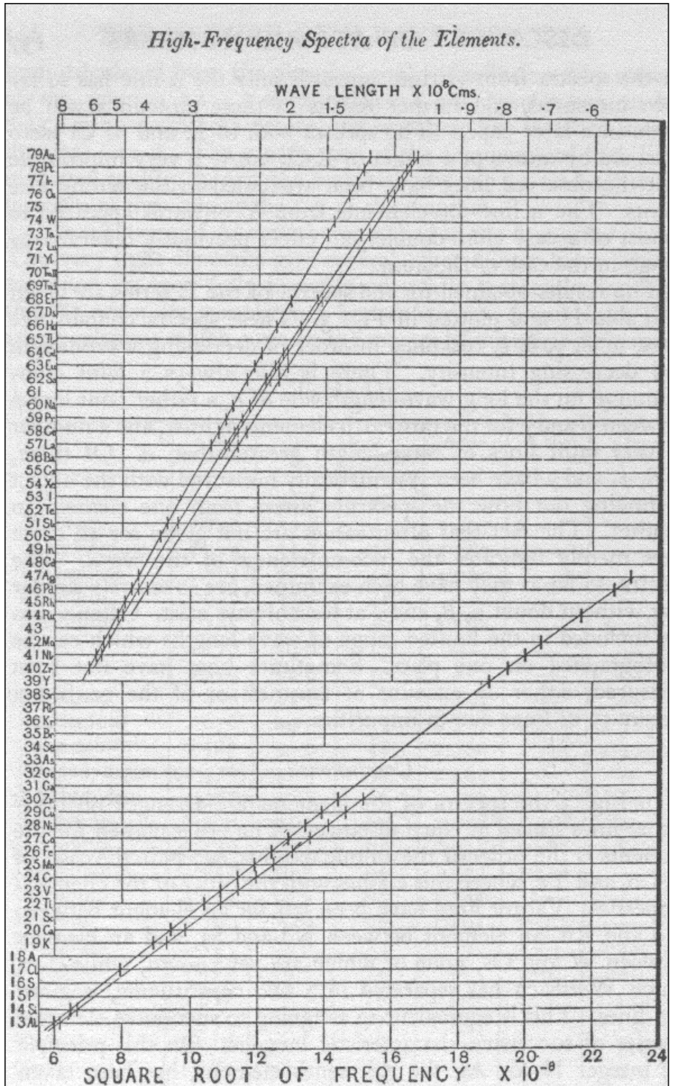


Fig. 3.

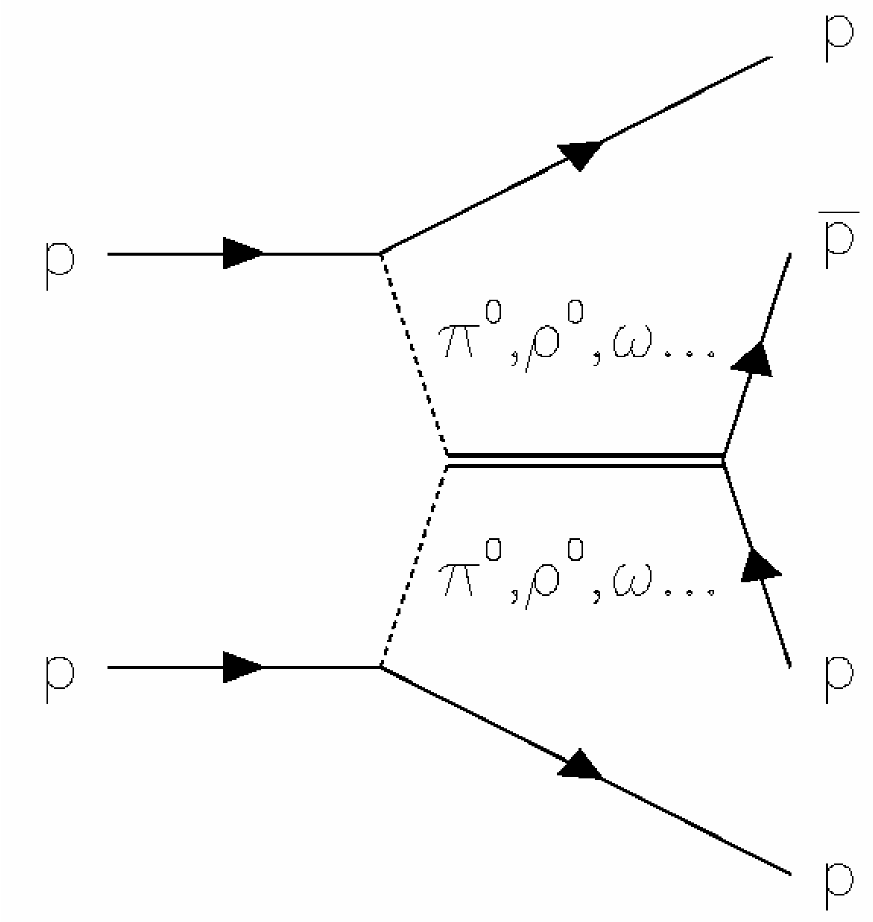
- Moseley observed linear relationship between K_α frequency and N^2 of element
- Atomic number had physical meaning
- Rutherford later interpreted N as Charge of nucleus

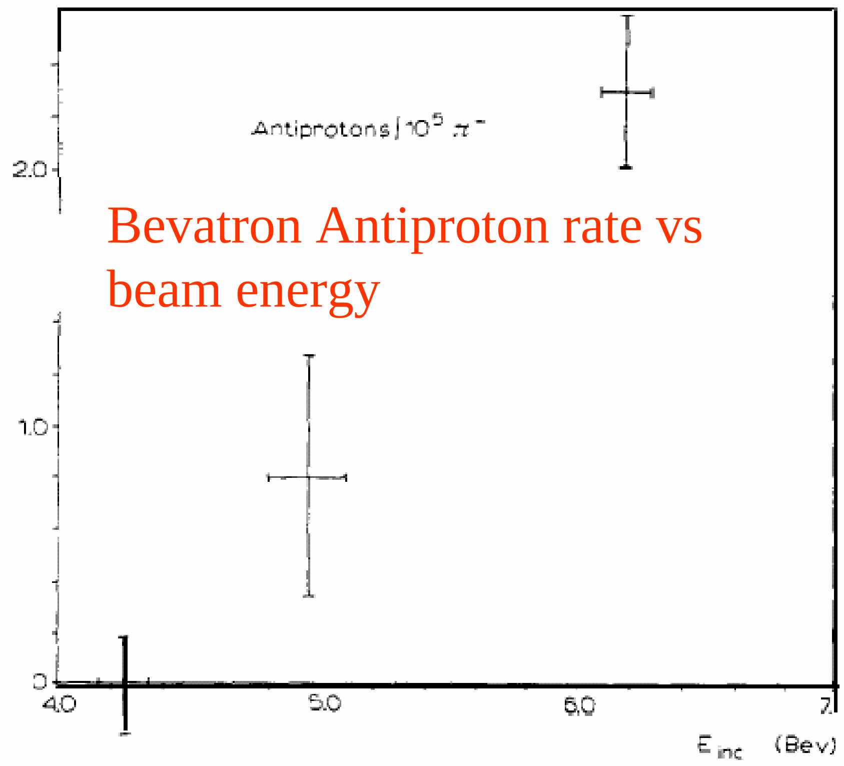
Particle Discoveries of early 20^{th} century

- x-ray (1895)
  - Result of cathode ray impacting matter
- electrons (1897)
  - orbit atomic nucleus
- proton (1911)
  - nucleus of lightest atom
- neutron (1932)
  - neutral constituent of the nucleus
- photon (1905)
  - quantum of the electromagnetic field

Antiproton production mechanism

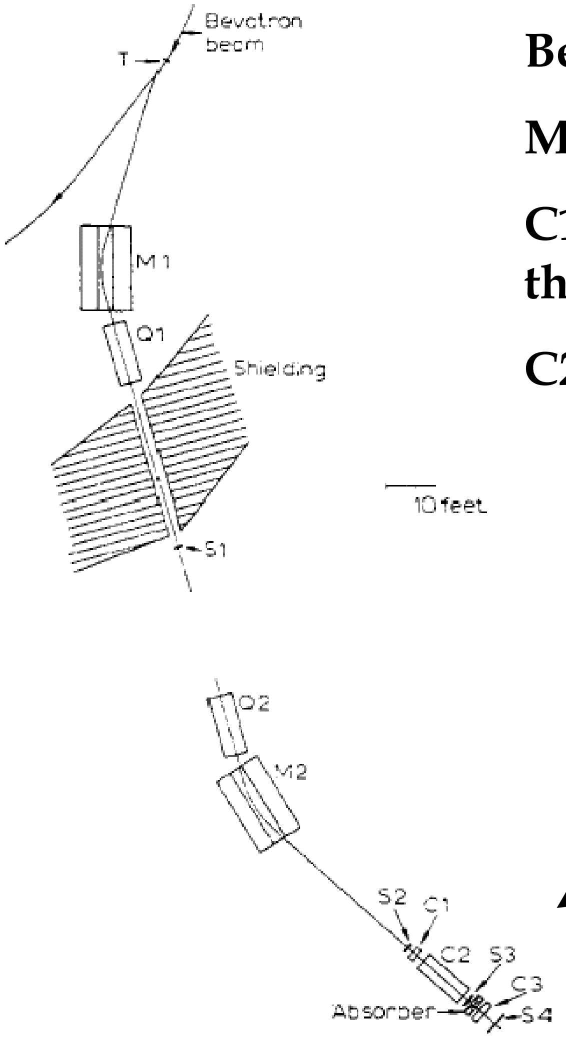
$p\,p \rightarrow p\,\bar{p}\,p\,p$ with $\bar{p}$ = anti-proton





Bevatron Antiproton rate vs beam energy

Chamberlain Discovery of Antiproton - 1955

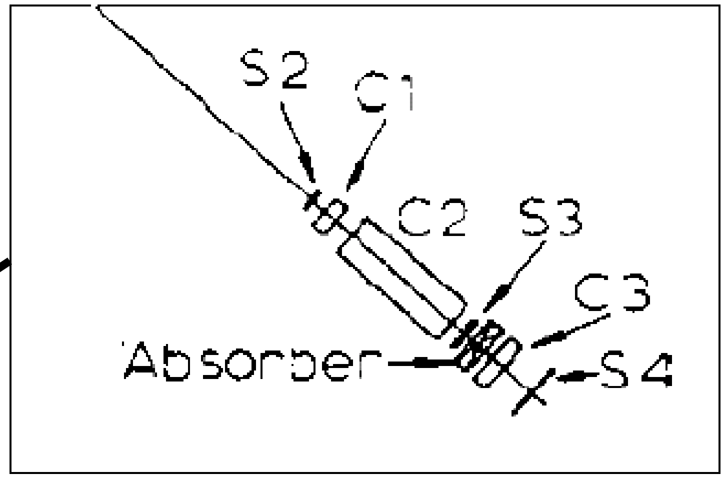


Bevatron protons energy = 6.2 GeV

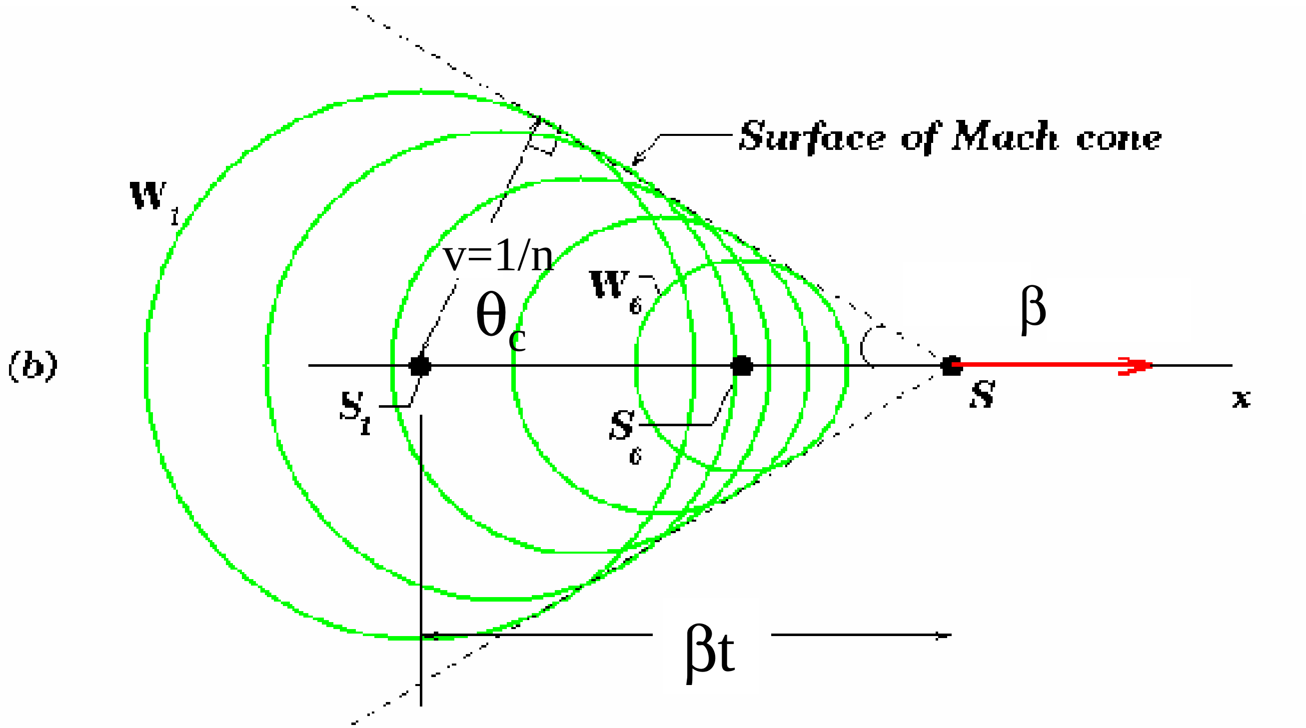
Momentum selection to 1.13 GeV/C

C1 is veto cerenkov counter, set to have threshold at β = 0.78

C2 is differential cerenkov, 0.75< β <0.78



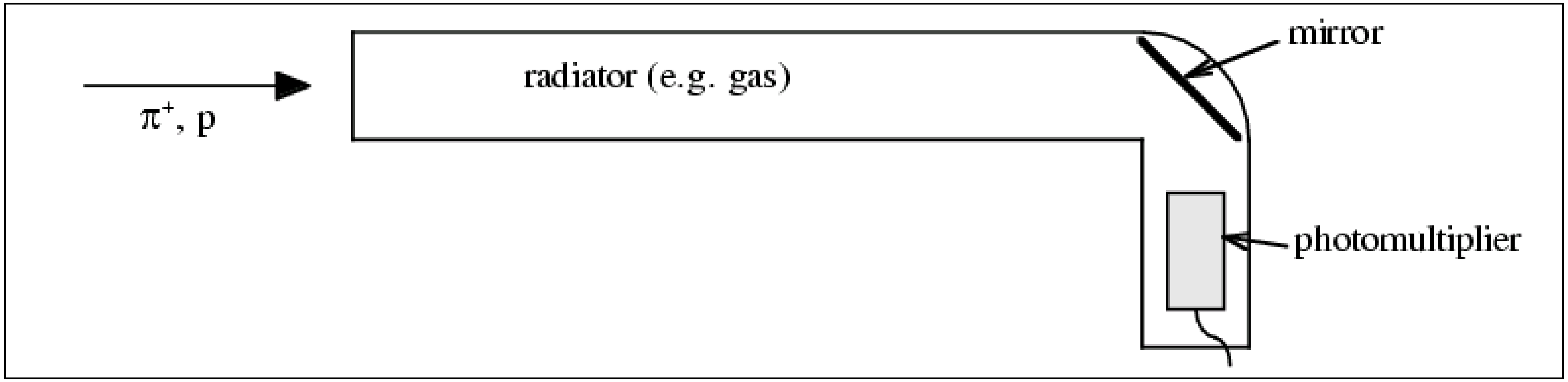
Cerenkov Effect



Cerenkov effect same as supersonic shockwave. When particle moves at speed faster than speed of light in medium (1/n), generates Cerenkov radiation. Characteristic angle

$\cos\theta_c = 1/\beta n$ for $\beta > 1/n$

Threshold Cerenkov Counters (C1)



ß = v/c = p/E ~ 1 - M²/(2*p²)

$$(n-1) = (n_0 - 1) \cdot \frac{P}{P_0}$$

Refractive indices vary in the range of 1 to 2.

Material	n	γ_{Th}
glass	1.46 to 1.75	1.22 to 1.37
scintillator	1.4 to 1.6	1.3 to 1.4
water	1.33	1.52
silica aerogel	$1 + (2 \text{ to } 10 \times 10^{-2})$	2 to 5
pentane (at S.T.P.)	$1 + 1.7 \times 10^{-3}$	17
carbon dioxide (at S.T.P.)	$1 + 4.3 \times 10^{-4}$	34
helium	$1 + 3.3 \times 10^{-5}$	123

Chamberlain Discovery of Antiproton

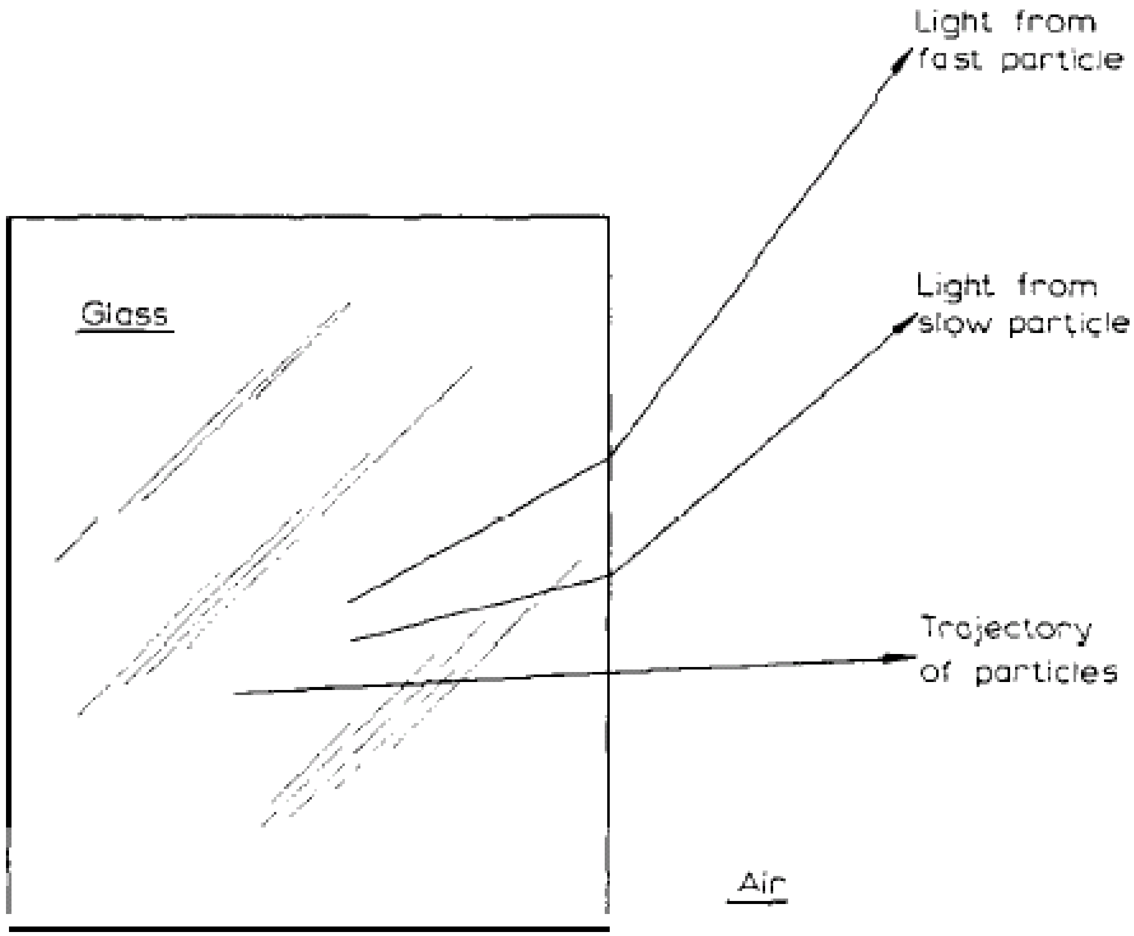
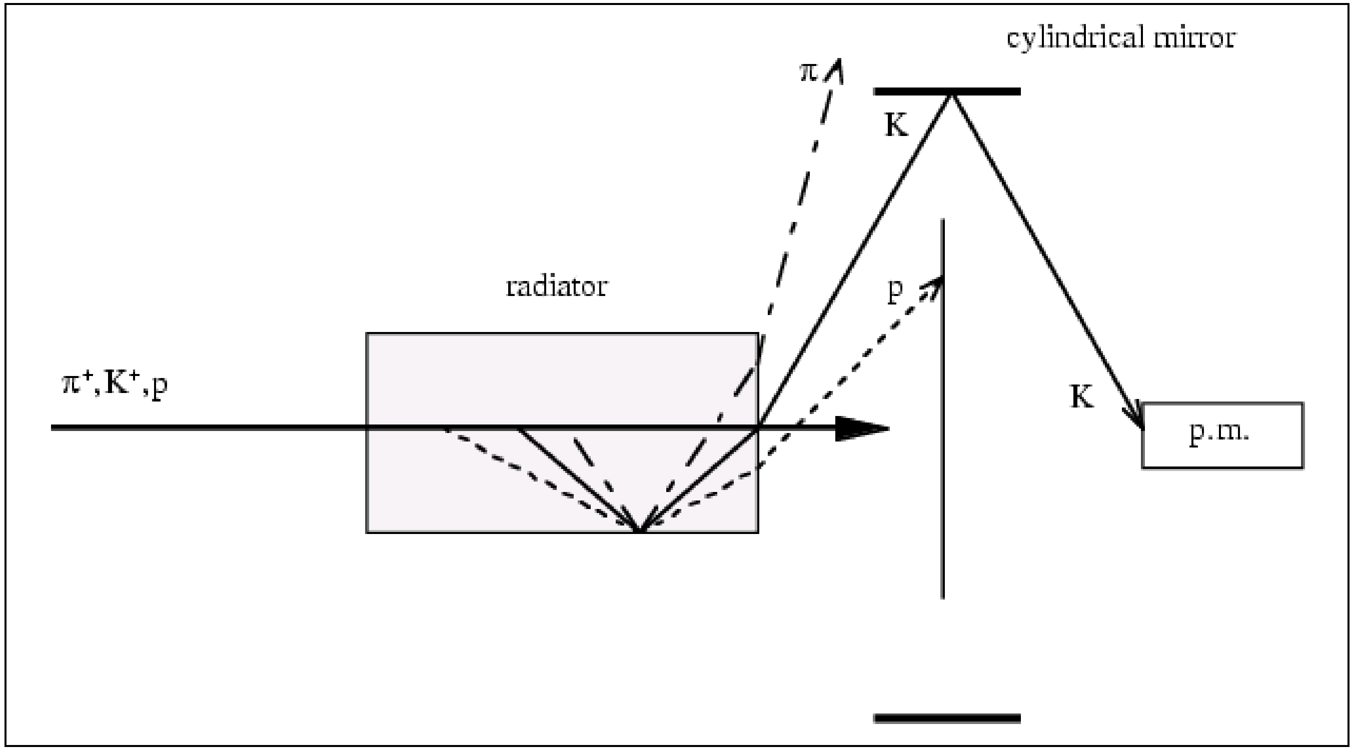


Fig. 6. Refraction of Čerenkov radiation at the interface between glass and air.

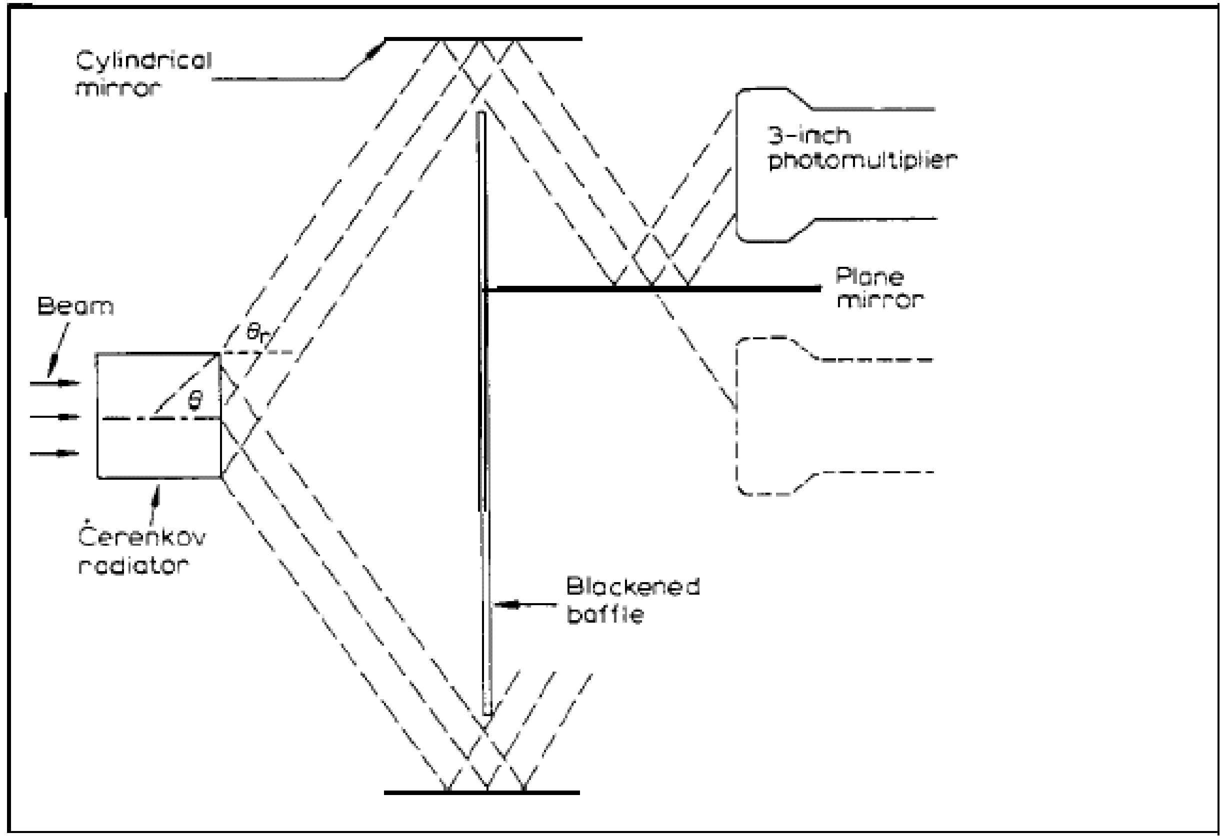
Differential Cerenkov Counter (C2)



A Differential Cherenkov detector only gives a signal for particles with a certain range of β (corresponding, for a given momentum, to a given range in mass).

Chamberlain Discovery of Antiproton

1959 O.CHAMBERLAIN



Velocity-selecting Cerenkov counter (C 2)

Fig. 7. View of the velocity-selecting Čerenkov counter.

Chamberlain Discovery of Antiproton – time of flight

Trigger

Pion: C2*S1*S2*C1

Pbar: C2*S1*S2*C1(bar)

Acc: S1*S2

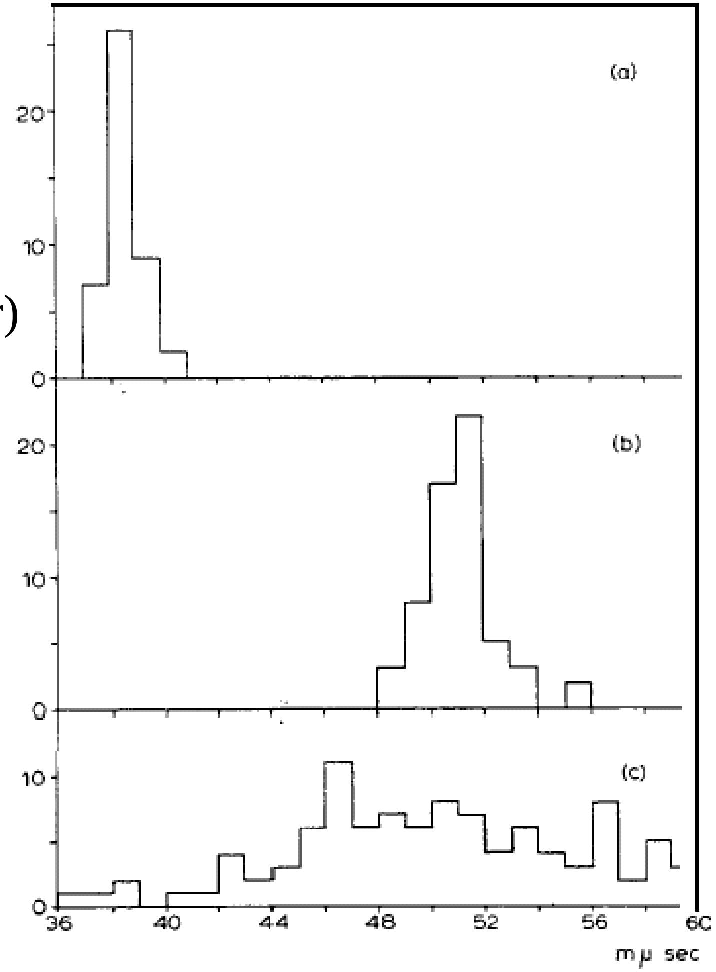


Fig. 10. (a) Histogram of times of flight for mesons; (b) histogram of times of flight for antiprotons; (c) apparent flight times for accidental coincidences.

S1 and S2 separated by 12 meters:

Pion $\delta(t)$ = 40 ns

Pbar $\delta(t)$ = 51 ns

Hofstadter and Internal Structure of Proton

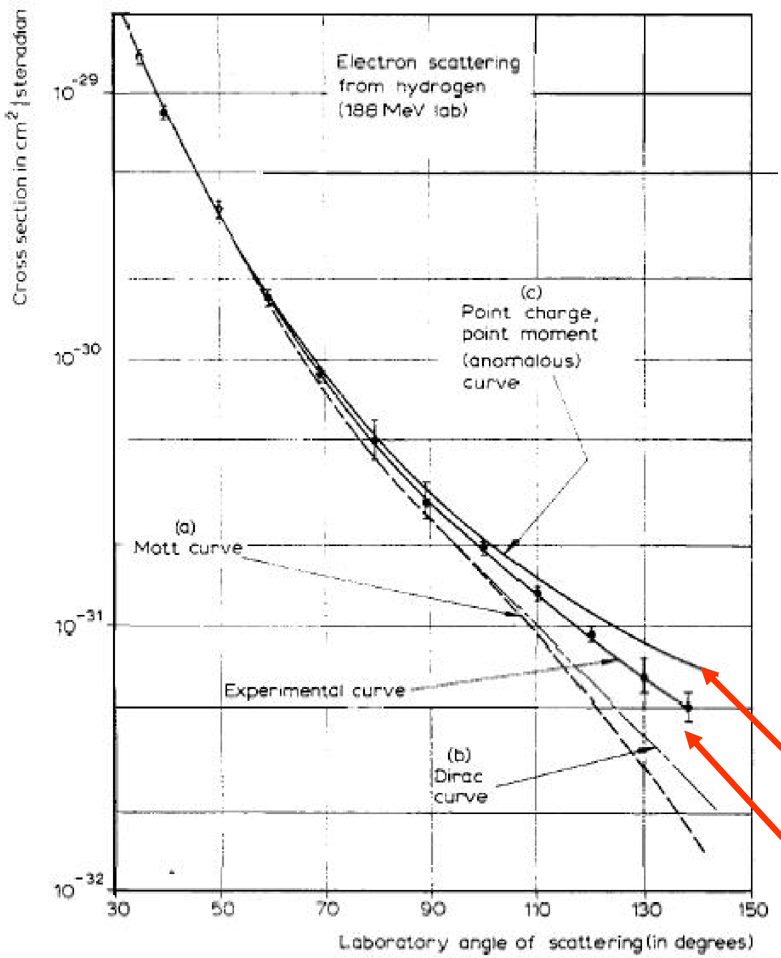


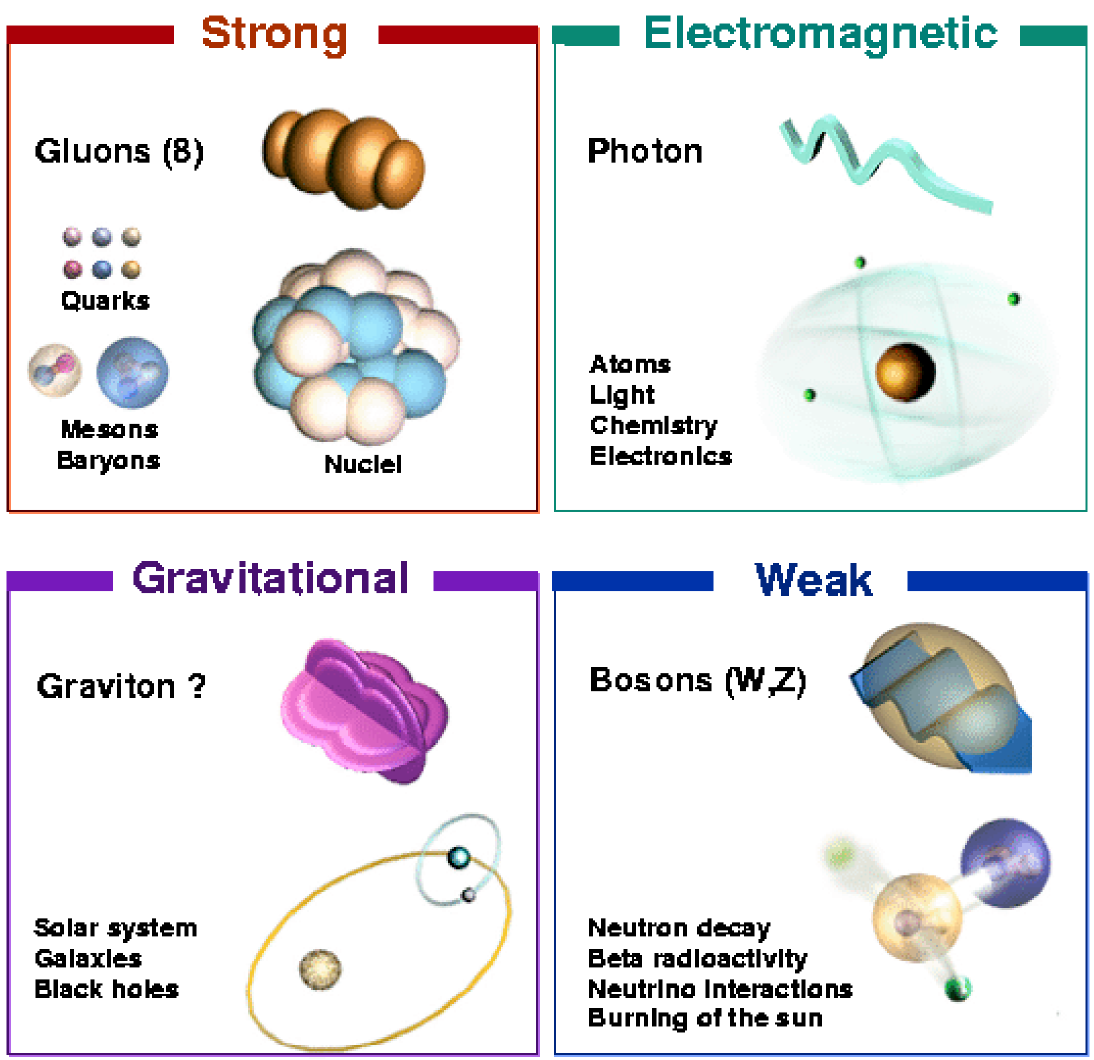
Fig. 9. Electron scattering from the proton at an incident energy of 188 MeV. *Curve (a)* shows the theoretical Mott curve for a spinless point proton. *Curve (b)* shows the theoretical curve for a point proton with a Dirac magnetic moment alone. *Curve (c)* shows the theoretical behavior of a point proton having the anomalous Pauli contribution in addition to the Dirac value of the magnetic moment. The deviation of the experimental curve from the Curve (*c*) represents the effect of form factors for the proton and indicates structure within the proton. The best fit in this figure indicates an rms radius close to $0.7 \cdot 10^{-13}$ cm.

- 188 MeV e-hydrogen elastic scattering
- Data falls below theoretical curve expected for point particle. (Reminds you of Thompson scattering model where large angle scattering was suppressed).
- Indicates proton has structure, not a point.

Point Charge Theory

Data

Forces



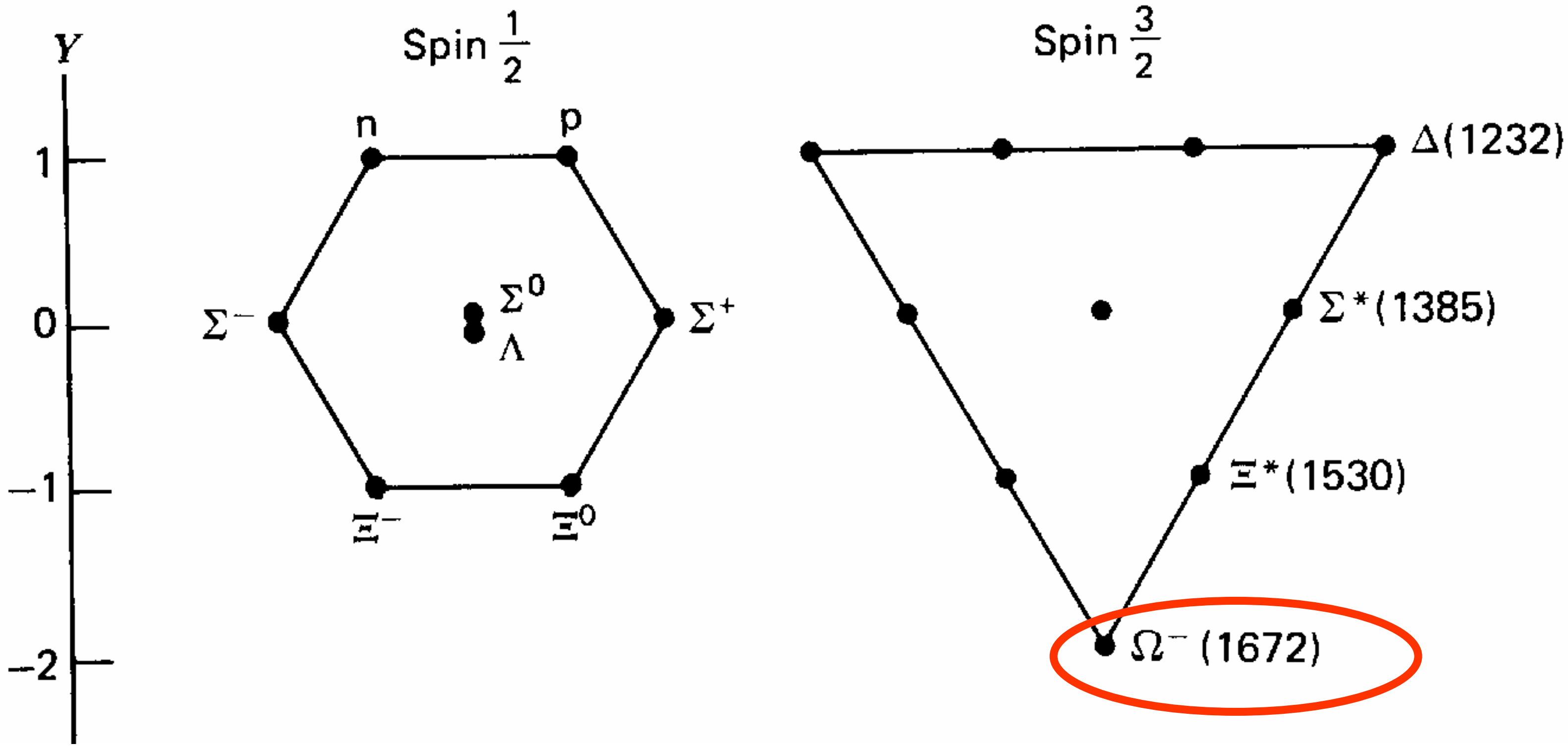
The particle drawings are simple artistic representations

Conserved Quantities

- Fundamental Physics Conservation Laws
  - Energy Conservation
  - Conservation of Momentum
  - Conservation of Angular Momentum
  - Pauli Exclusion Principle
- Universal Particle Physics Conservation Laws
  - Baryon Number:
    - 1/3 for quarks, -1/3 antiquarks
  - Lepton Number
    - Separate Number for each family of leptons.
  - Charge Conservation

8-fold Way (periodic table for particles)

- Developed by Murray Gell-Mann and Yuval Ne'eman in 1961
- Plot *hypercharge* Y (baryon number + strangeness) versus *isospin*
- Observe patterns in multiplets
- Omega predicted and observed 1964



The quark model

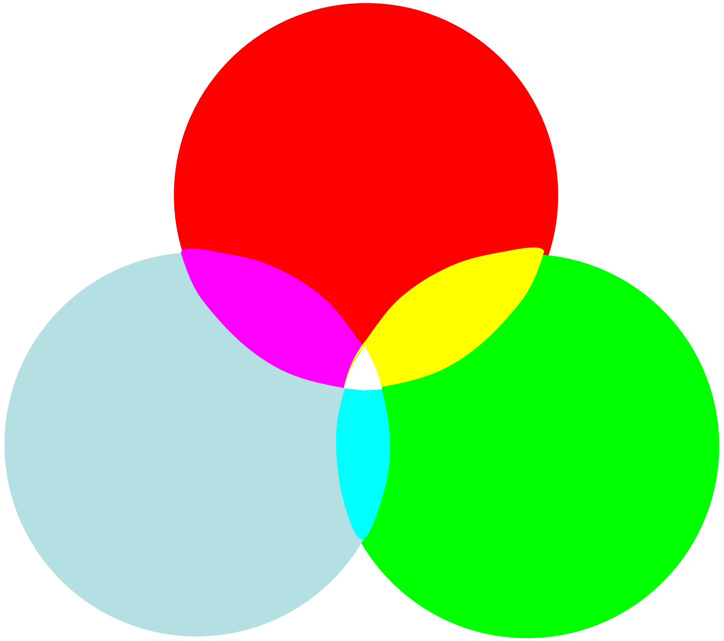
- 1964 Gell-Mann, Zweig
  - there are three quarks and their antiparticles

Quark	Up	Down	Strange
Charge	+2/3	-1/3	-1/3

  - each quark can carry one of three colors
    - red blue green
  - antiquarks carry anticolor
    - anti-red anti-blue anti-green

The quark model

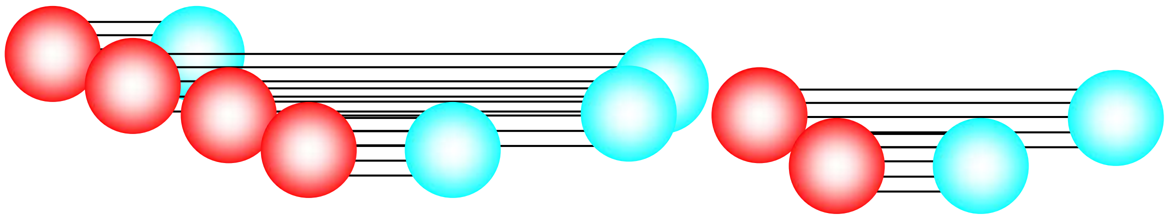
- only colorless (“white”) combinations of quarks and antiquarks can form particles
  - qqq
  - $\bar{q}q$



  - no others observed

Quark confinement

- What holds quarks/antiquarks together?
  - strong force
  - acts between all “colored” objects
  - short range
  - independent of distance



Motivation for idea of "quarks"

- People noticed regular pattern of properties of different particles
- Murray Gell-Mann and George Zweig propose in 1964 that mesons and baryons are not elementary, but are composed of smaller constituents: *Quarks*
- James Joyce, *Finnegan's Wake*:
  "Three quarks for Muster Mark."
- *u*, *d*, and *s* quarks (*up, down, strange*)
- These quarks have spin 1/2, and have fractional electric charge (2/3, -1/3)

- Proton: u u d
- Neutron: u d d
- Pion: ud, uu - dd, du
- Kaon: us, ds, sd, su

- At the time, not clear if a mathematical convenience, or reality

Quarks (spin ½)

Particle	Symbol	Mass (MeV/c^2)	Electric Charge

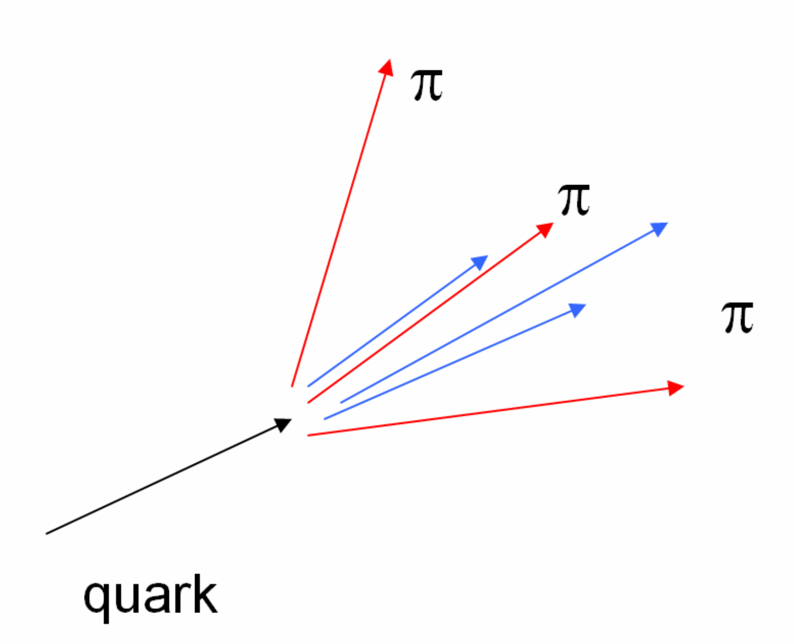
Quarks			
down	d	5-15	- 1/3
up	u	2-8	2/3
strange	s	100-300	- 1/3
charm	c	1300-1700	2/3
bottom	b	4700-5300	- 1/3
top	t	175,000	2/3

History of Discovery of Quarks

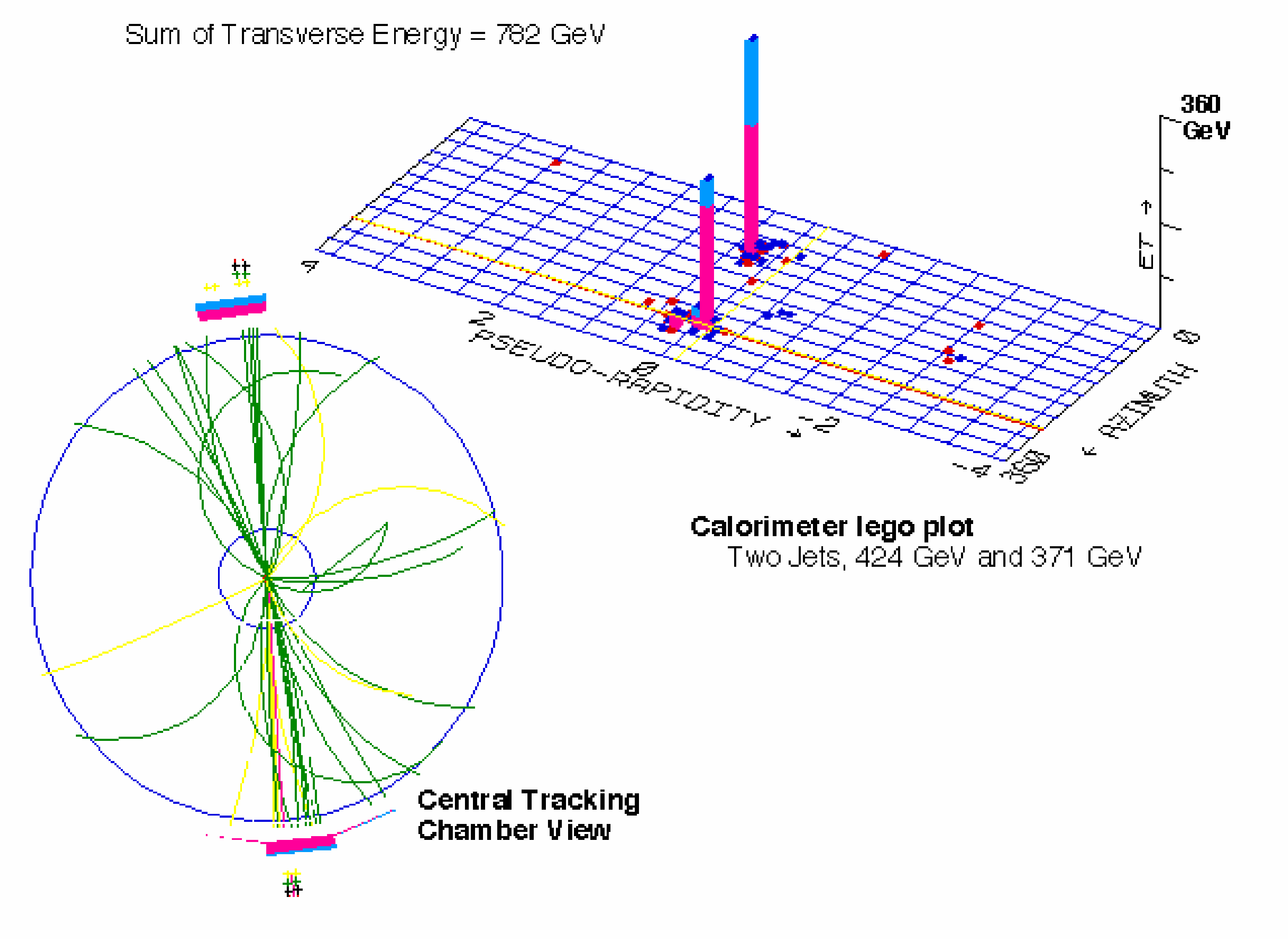
- SLAC, 1968
  - Discovery of quarks in electron-proton scattering
- SLAC and Brookhaven, 1974
  - Discovery of the charm quark in electron-positron annihilation
- Fermilab, 1977
  - Discovery of the bottom quark in proton collisions
- Fermilab, 1995
  - Discovery of the top quark in proton-antiproton annihiliation

Jets

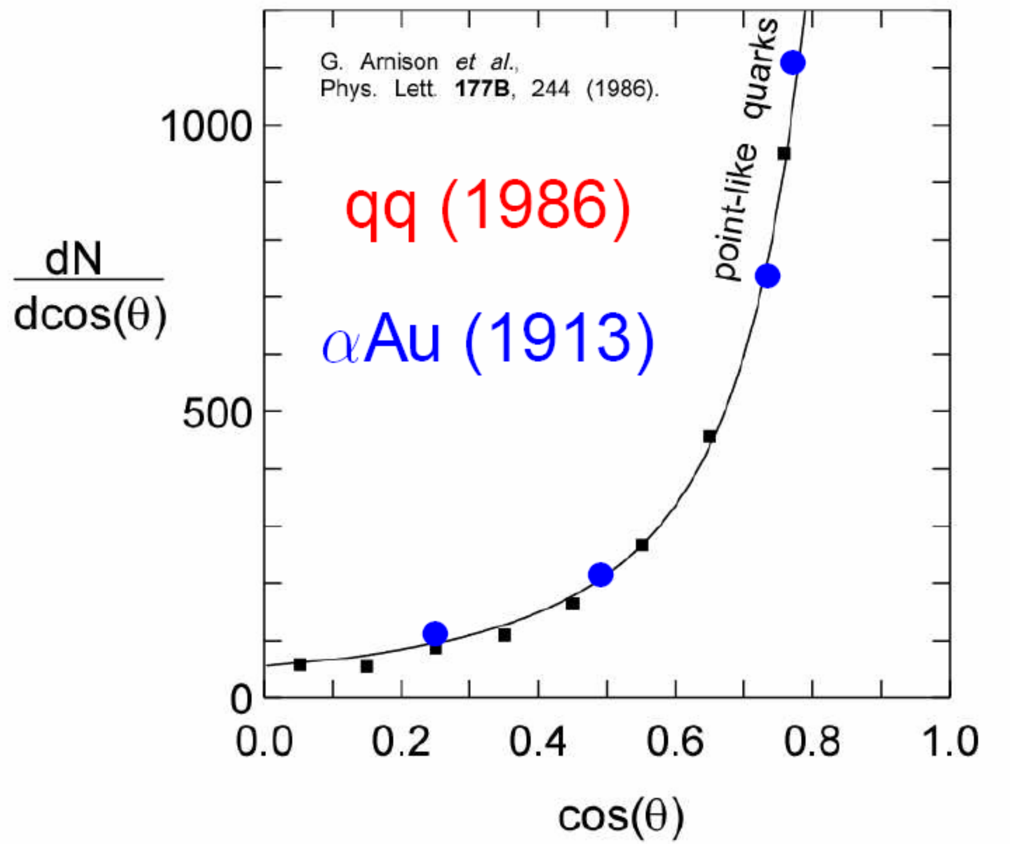
- No one has actually seen a single bare quark!
- Instead, we observe clusters of known particles (*Jets*) which travel in the direction of the scattered quark
- These jets behave as if they originated from a spin 1/2 quark.



CDF 2-jet Event



UA1 di-jet measurement



$$\frac{d\sigma}{d\cos\theta} \sim \alpha_s^2 \left(\frac{\hbar c}{E_{CM}}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

demonstrating:

- $1/r^2$ strong force
- spin 1 gluon
- pointlike quarks

Rutherford data for αAu also plotted. Remember Rutherford Scattering eqn.

Leptons (spin ½)

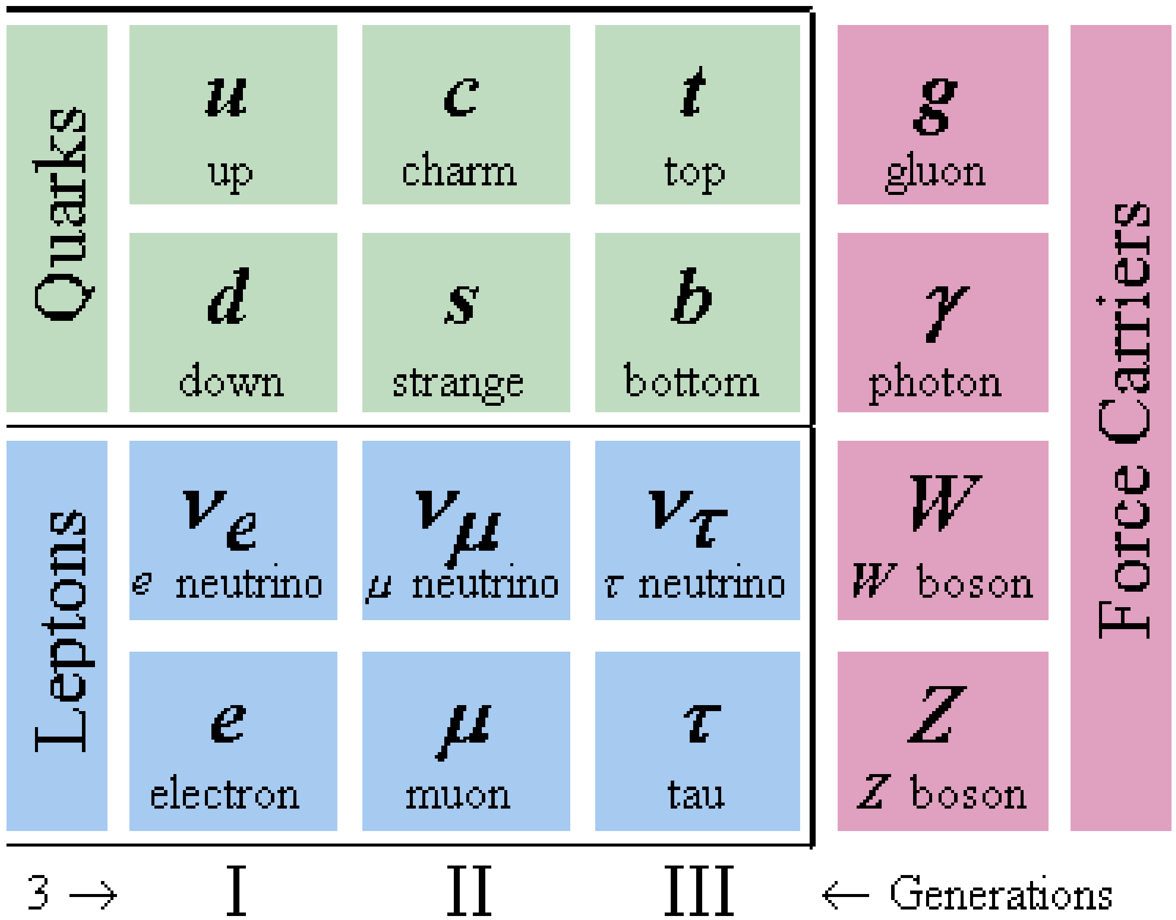
Leptons			
Particle	Symbol	Mass (MeV/c ^{2})	Electric Charge
electron	e^-	0.511	-1
muon	μ^-	105.7	-1
tau	τ	1784.1	-1
electron neutrino	ν_e	$<7.3\times10^{-6}$	0
muon neutrino	ν_μ	<0.27	0
tau neutrino	ν_τ	<35	0

Gauge Particles (spin 1)

Particle	Symbol	Mass (MeV/c ^{2})	Electric Charge
Gauge Bosons			
photon	γ	0	0
gluon	g	0	0
W-boson	W	80,200	1
Z-boson	Z	91,170	0

Elementary particles

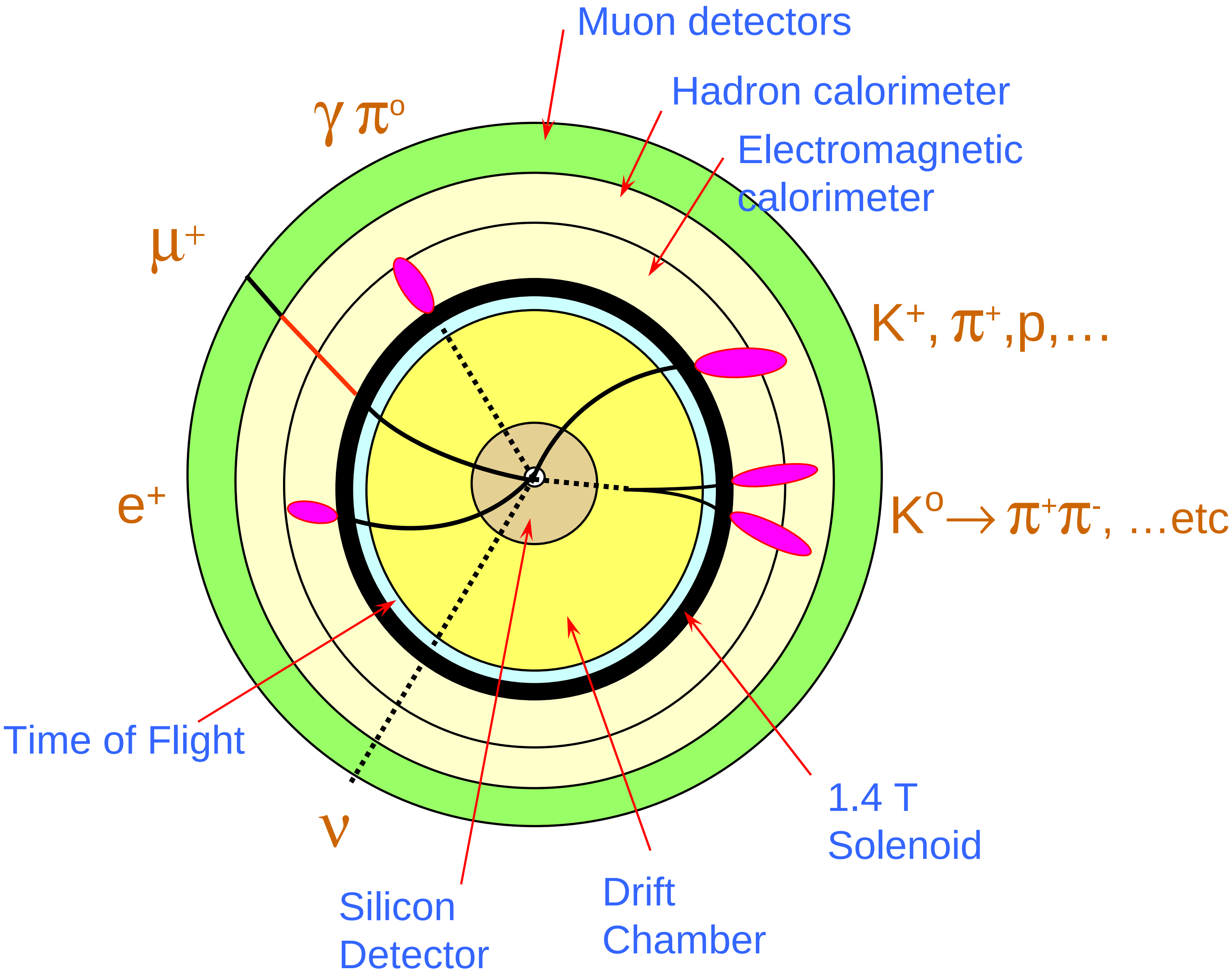
- All elementary particles of standard model observed
- (Except Higgs)
- ν_τ observed in 2000
- Higgs will be discovered at LHC?



Detector Subsystems

Particle type	Tracking	ECAL	HCAL	Muon
γ				
e				
μ				
Jet				
Et miss				

Collider Detector CDF Functional Schematic



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