

INTRODUCTION TO PARTICLE PHYSICS

From atoms to quarks

An elementary historical review of concepts, discoveries
and achievements

Recommended reading:

D.H. Perkins, *Introduction to High Energy Physics*

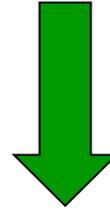
F.E. Close, *The cosmic onion*

The “elementary particles” in the 19th century:

The Atoms of the 92 Elements

1. Hydrogen
2. Helium
3. Lithium
-
-
92. Uranium

$$\text{Mass } M_{\text{H}} \approx 1.7 \times 10^{-24} \text{ g}$$



increasing mass

$$\text{Mass} \approx 238 M_{\text{H}}$$

Estimate of a typical atomic radius

$$\text{Number of atoms /cm}^3: \quad n = \frac{N_{\text{A}}}{A} \rho$$

$$\left(\begin{array}{l} N_{\text{A}} \approx 6 \times 10^{23} \text{ mol}^{-1} \text{ (Avogadro constant)} \\ A: \text{ molar mass} \\ \rho: \text{ density} \end{array} \right)$$

$$\text{Atomic volume: } V = \frac{4}{3} \pi R^3$$

$$\text{Packing fraction: } f \approx 0.52 \text{ — } 0.74$$



$$\rightarrow R = \left(\frac{3f}{4\pi n} \right)^{1/3}$$

Example: Iron ($A = 55.8 \text{ g}$; $\rho = 7.87 \text{ g cm}^{-3}$)

$$R = (1.1 \text{ — } 1.3) \times 10^{-8} \text{ cm}$$

1894 – 1897: Discovery of the electron

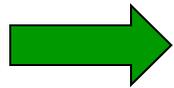
Study of “cathode rays”: electric current in tubes at very low gas pressure (“glow discharge”)

Measurement of the electron mass: $m_e \approx M_H/1836$

“Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?” (J.J. Thomson)



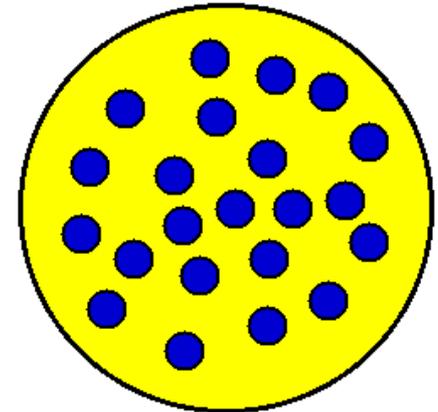
J.J. Thomson



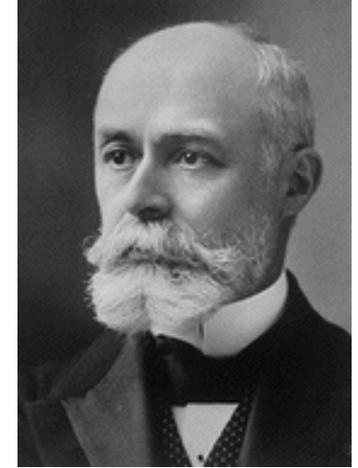
ATOMS ARE NOT ELEMENTARY

Thomson's atomic model:

- Electrically charged sphere
- Radius $\sim 10^{-8}$ cm
- Positive electric charge
- Electrons with negative electric charge embedded in the sphere

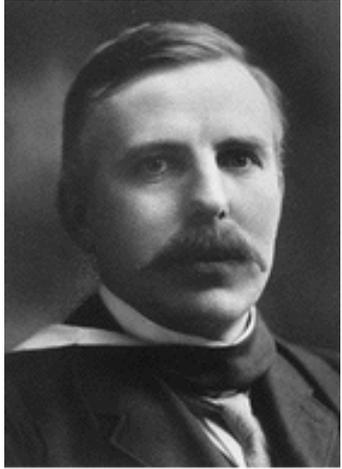


1896: Discovery of natural radioactivity (Henri Becquerel)

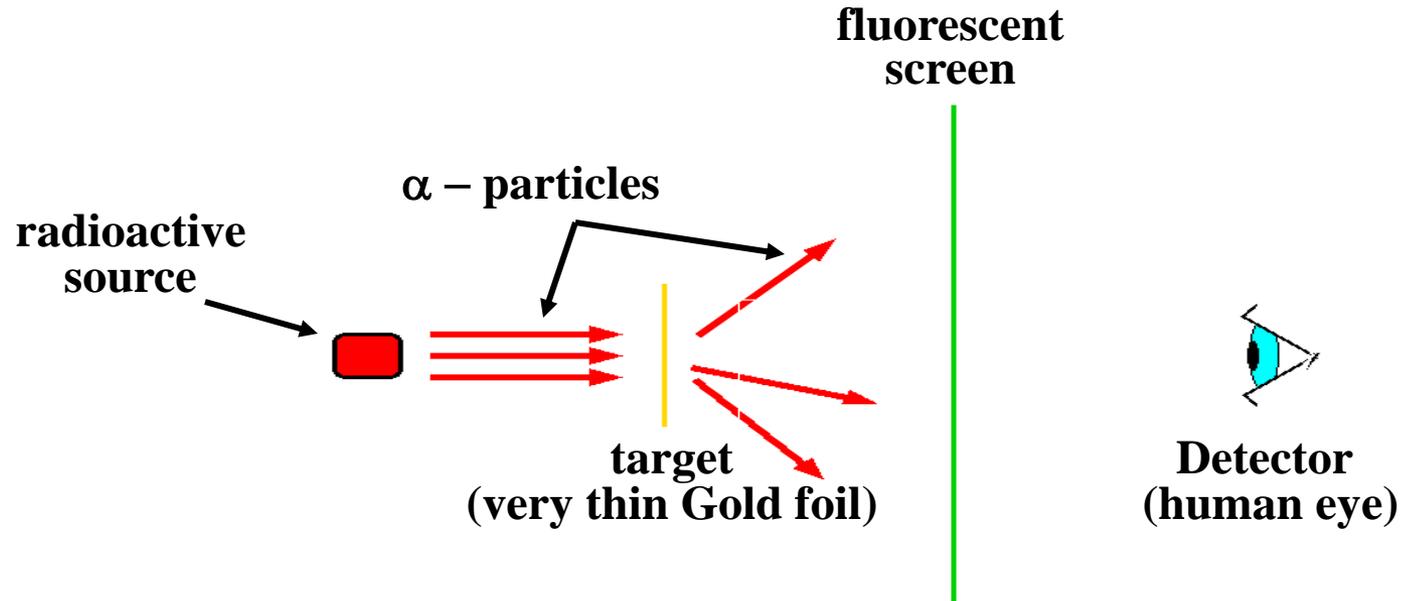


Henri Becquerel

1909 – 13: Rutherford's scattering experiments Discovery of the atomic nucleus



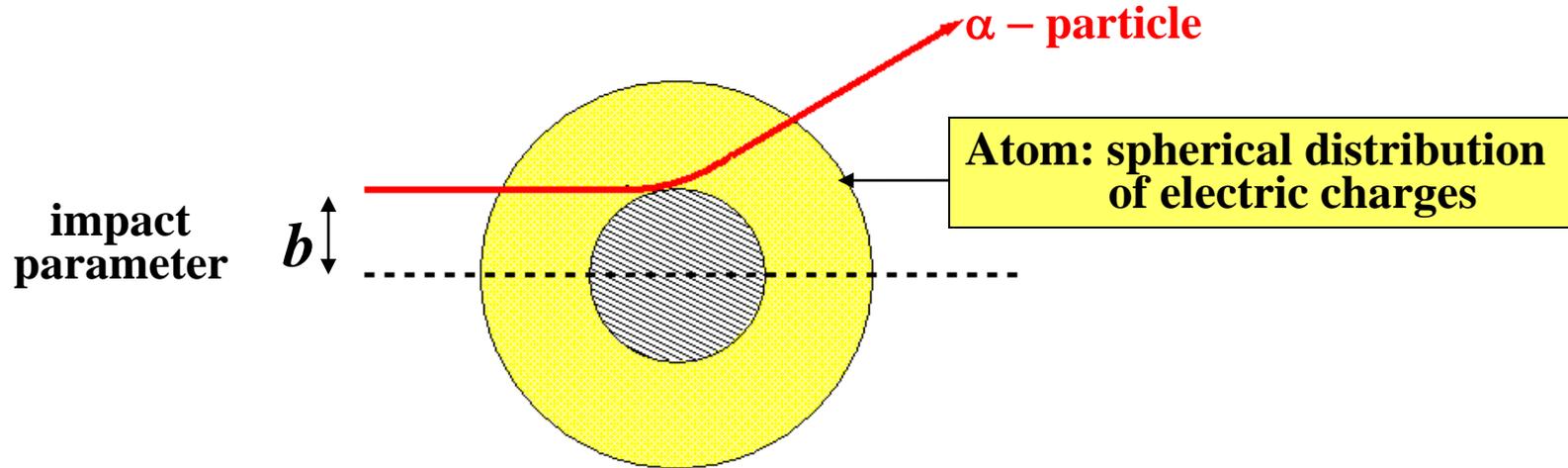
Ernest Rutherford



α - particles : nuclei of Helium atoms spontaneously emitted by heavy radioactive isotopes
Typical α - particle velocity $\approx 0.05 c$ (c : speed of light)

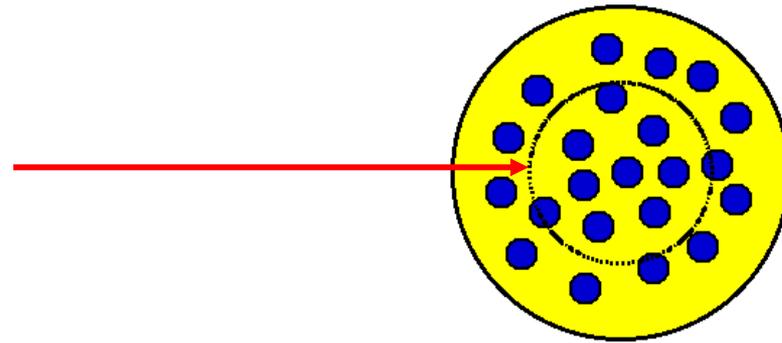
Expectations for α – atom scattering

α – atom scattering at low energies is dominated by Coulomb interaction



α – particles with impact parameter = b “see” only electric charge within sphere of radius = b (Gauss theorem for forces proportional to r^{-2})

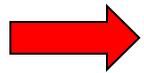
For Thomson’s atomic model
the electric charge “seen” by the
 α – particle is zero, independent
of impact parameter



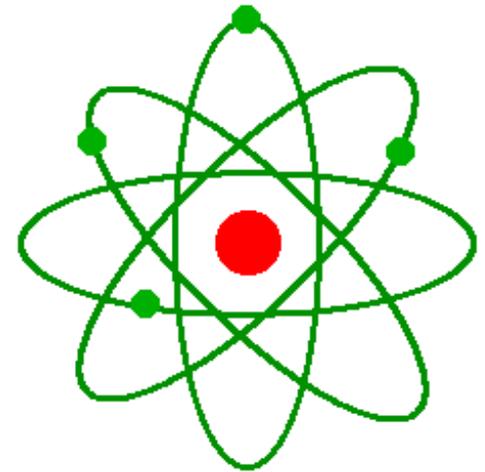
\Rightarrow no significant scattering at large angles is expected

Rutherford's observation:

significant scattering of α – particles at large angles, consistent with scattering expected for a sphere of radius \approx few $\times 10^{-13}$ cm and electric charge = Ze , with $Z = 79$ (atomic number of gold) and $e = |\text{charge of the electron}|$



**an atom consists of
a positively charged nucleus
surrounded by a cloud of electrons**



Nuclear radius $\approx 10^{-13}$ cm $\approx 10^{-5}$ x atomic radius

Mass of the nucleus \approx mass of the atom

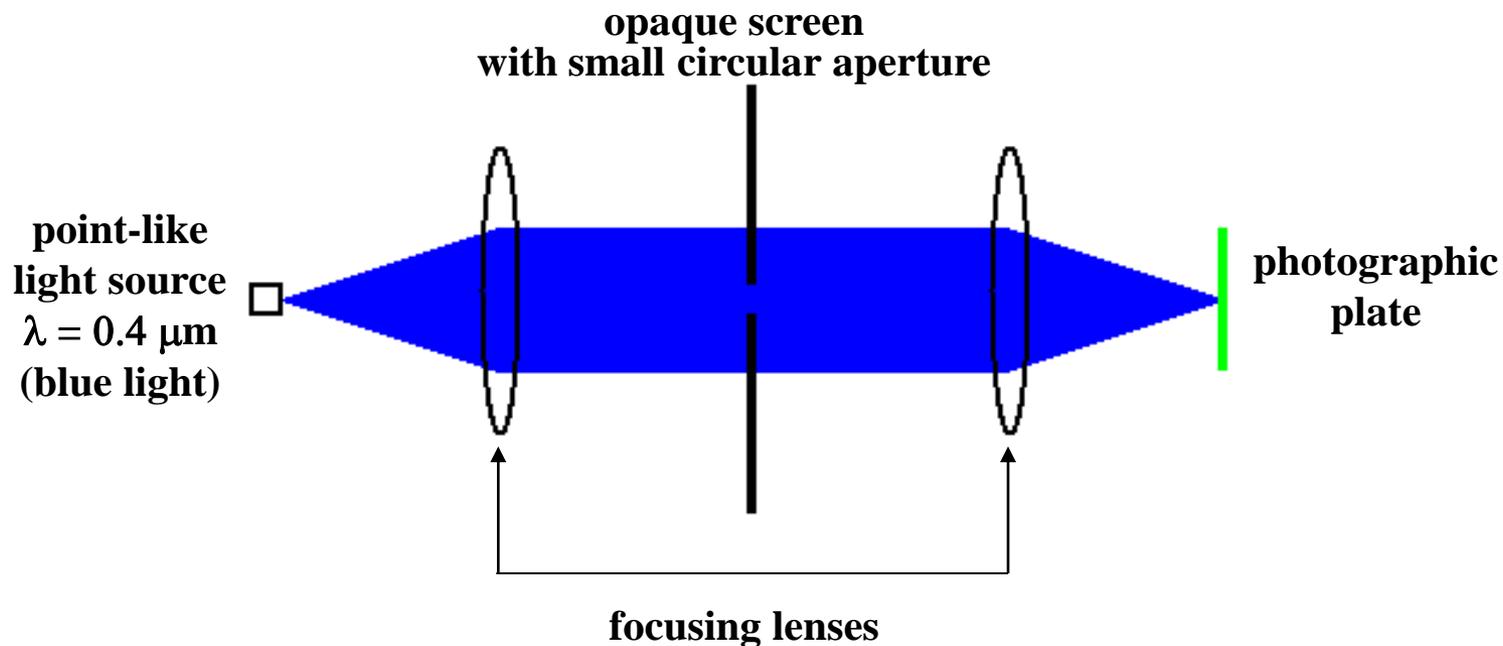
(to a fraction of 1‰)

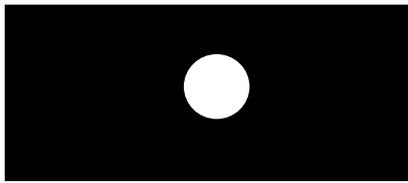
Two questions:

- Why did Rutherford need α – particles to discover the atomic nucleus?
- Why do we need huge accelerators to study particle physics today?

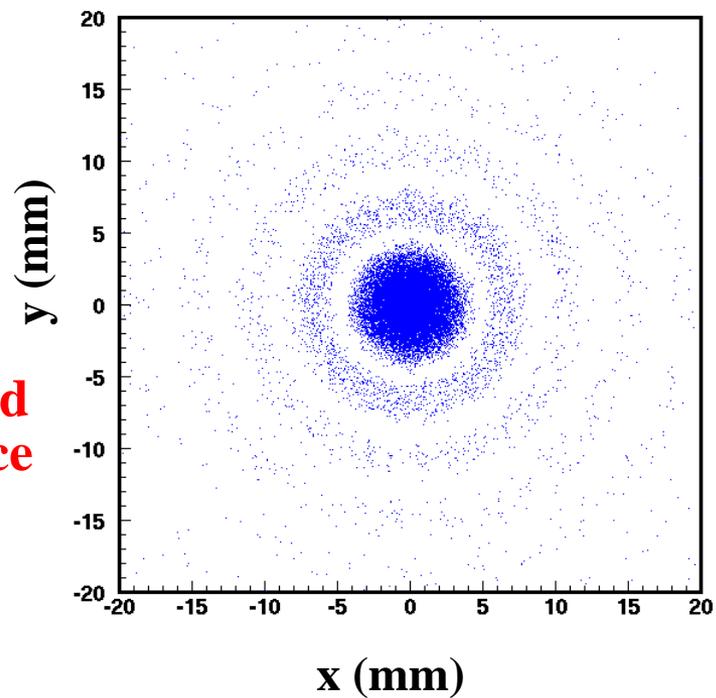
Answer to both questions from basic principles of Quantum Mechanics

Observation of very small objects using visible light





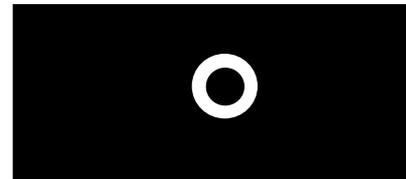
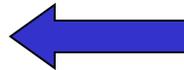
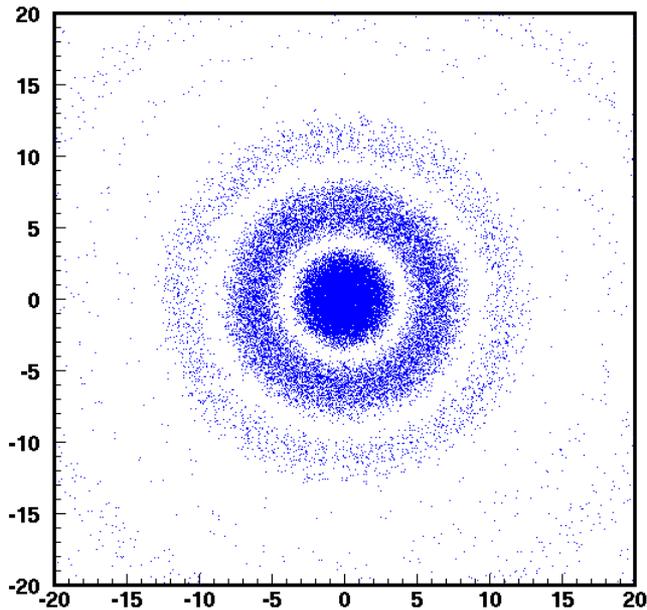
Aperture diameter: $D = 20 \mu\text{m}$
Focal length: 20 cm



Observation of light diffraction, interpreted as evidence that light consists of waves since the end of the 17th century

Angular aperture of the first circle (before focusing):

$$\alpha = 1.22 \lambda / D$$

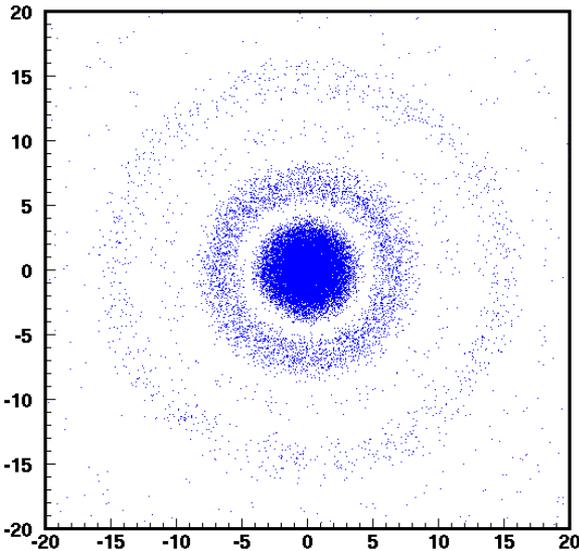


Opaque disk, diam. $10 \mu\text{m}$
in the centre

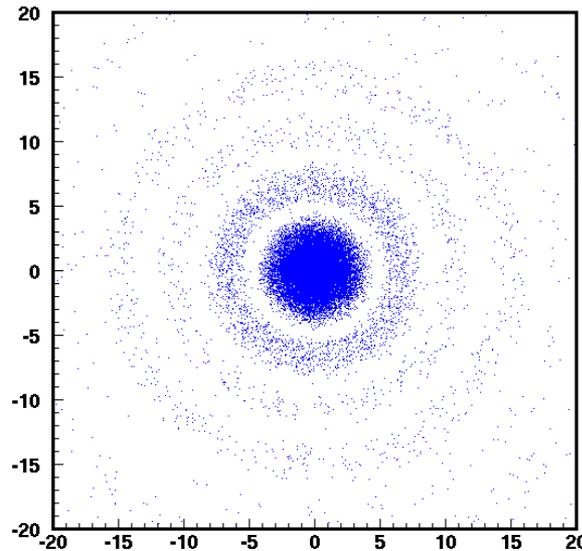
Presence of opaque disk is detectable

Opaque disk of variable diameter

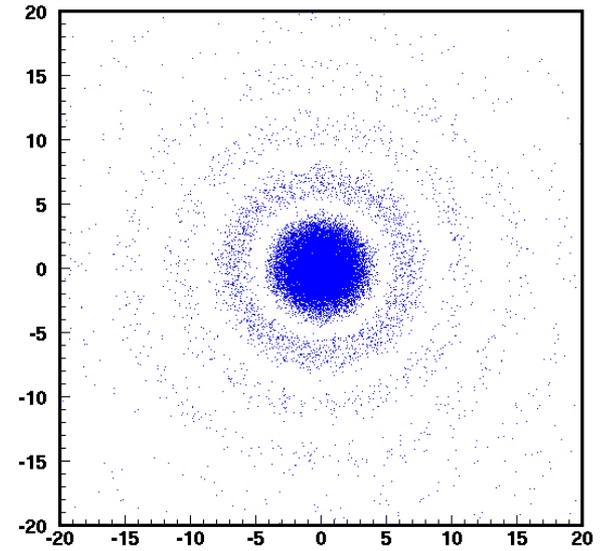
diameter = 4 μm



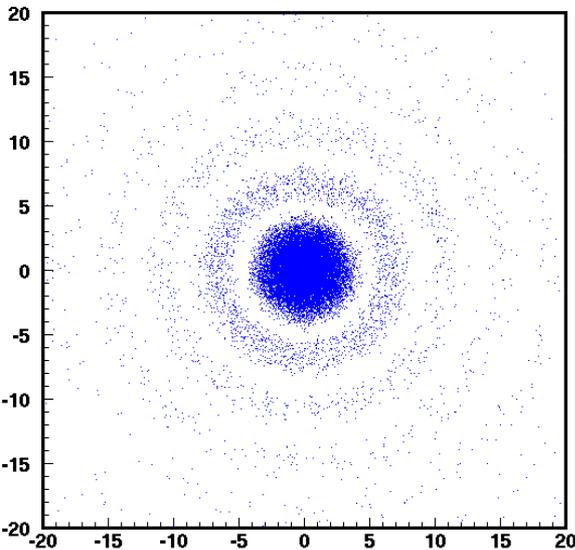
diameter = 2 μm



diameter = 1 μm



no opaque disk

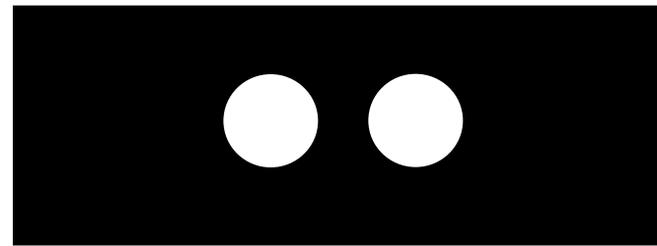


The presence of the opaque disk in the centre is detectable if its diameter is larger than the wavelength λ of the light

The RESOLVING POWER of the observation depends on the wavelength λ

Visible light: not enough resolution to see objects smaller than 0.2 – 0.3 μm

Opaque screen with two circular apertures



aperture diameter: $10\ \mu\text{m}$
distance between centres: $15\ \mu\text{m}$

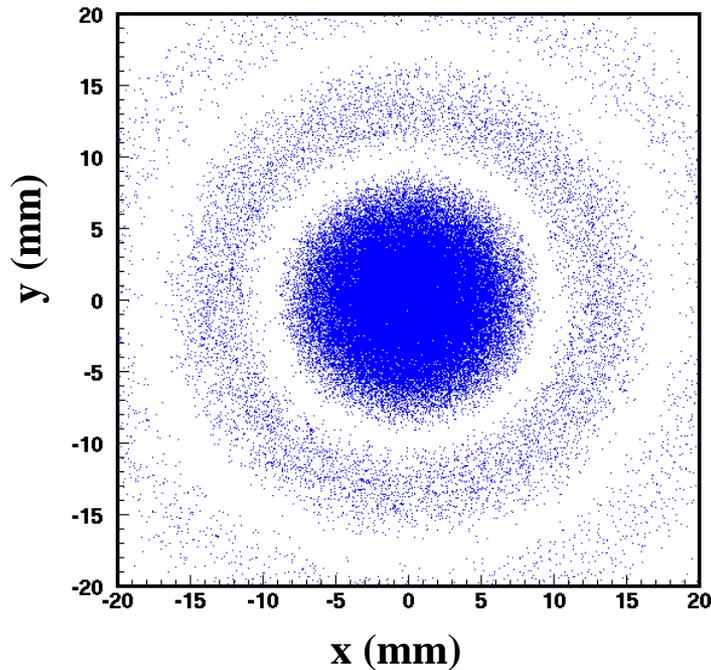


Image obtained with both apertures open simultaneously

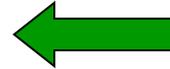
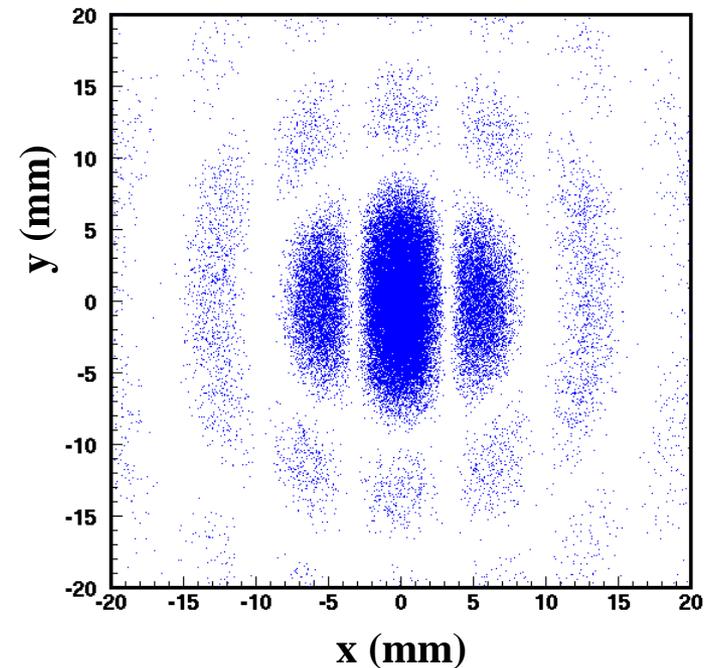
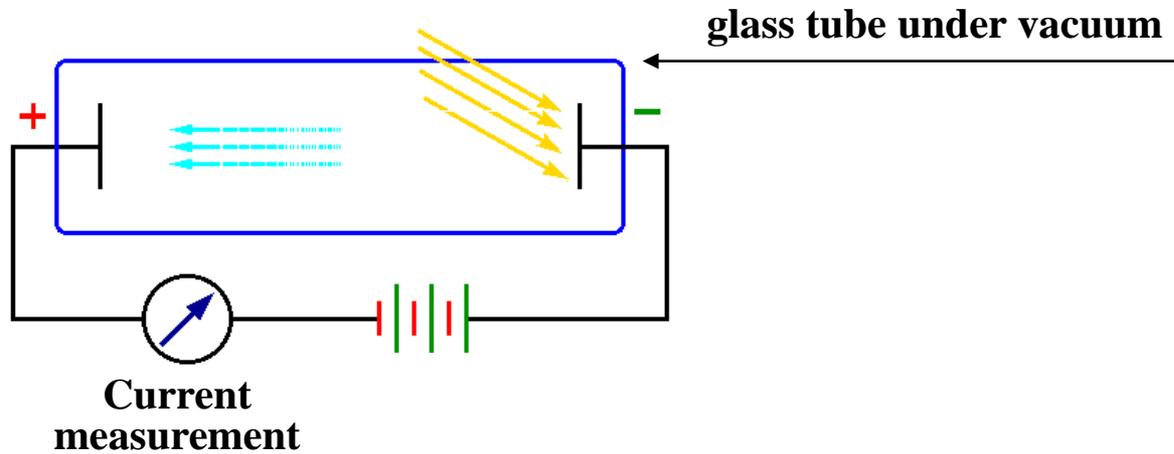


Image obtained by shutting one aperture alternatively for 50% of the exposure time



Photoelectric effect: evidence that light consists of particles



Observation of a threshold effect as a function of the frequency of the light impinging onto the electrode at negative voltage (cathode):

Frequency $\nu < \nu_0$: electric current = zero, independent of luminous flux;

Frequency $\nu > \nu_0$: current > 0 , proportional to luminous flux

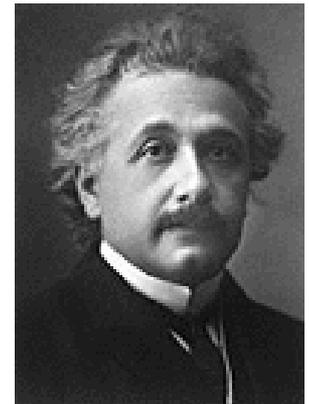
INTERPRETATION (A. Einstein):

- Light consists of particles (“photons”)
- Photon energy proportional to frequency:

$$E = h \nu$$

(Planck constant $h = 6.626 \times 10^{-34} \text{ J s}$)

- Threshold energy $E_0 = h\nu_0$: the energy needed to extract an electron from an atom (depends on the cathode material)



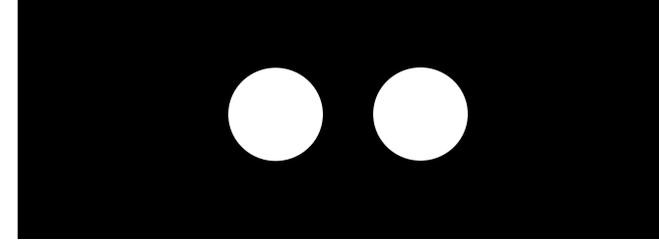
Albert Einstein

Repeat the experiment with two circular apertures using a very weak light source

Luminous flux = 1 photon /second

(detectable using modern, commercially available photomultiplier tubes)

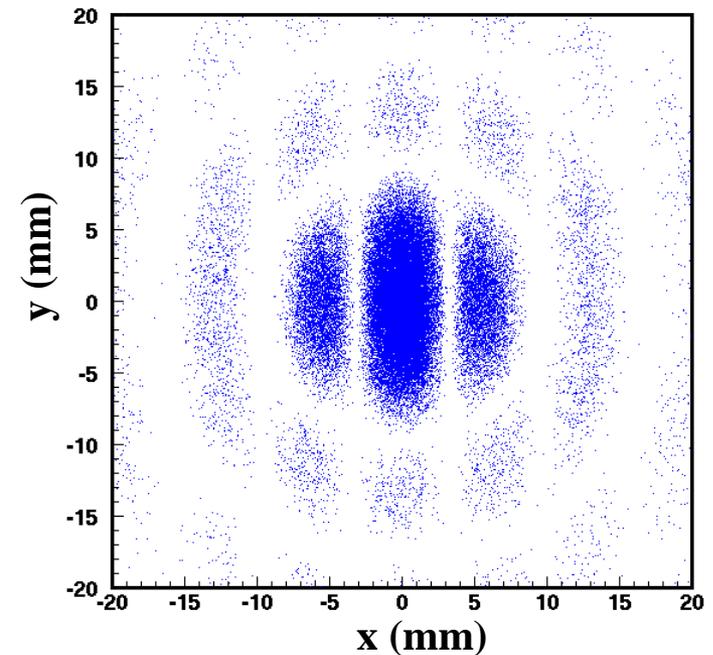
Need very long exposure time



aperture diameter: $10\ \mu\text{m}$
distance between centres: $15\ \mu\text{m}$

Question: which aperture will photons choose?

Answer: diffraction pattern corresponds to both apertures simultaneously open, independent of luminous flux



Photons have both particle and wave properties simultaneously

It is impossible to know which aperture the photon traversed

The photon can be described as a coherent superposition of two states

1924: De Broglie's principle

Not only light, but also matter particles possess both the properties of waves and particles

Relation between wavelength and momentum:

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

h : Planck constant

$p = m v$: particle momentum



Louis de Broglie

Hypothesis soon confirmed by the observation of diffraction pattern in the scattering of electrons from crystals, confirming the wave behaviour of electrons (Davisson and Germer, 1927)

Wavelength of the α – particles used by Rutherford in the discovery of the atomic nucleus:

$$\lambda = \frac{h}{m_{\alpha} v} \approx \frac{6.626 \times 10^{-34} \text{ J s}}{(6.6 \times 10^{-27} \text{ kg}) \times (1.5 \times 10^7 \text{ m s}^{-1})} \approx 6.7 \times 10^{-15} \text{ m} = 6.7 \times 10^{-13} \text{ cm}$$

α -particle mass $0.05 c$ \sim resolving power of Rutherford's experiment

Typical tools to study objects of very small dimensions

		Resolving power
Optical microscopes	Visible light	$\sim 10^{-4}$ cm
Electron microscopes	Low energy electrons	$\sim 10^{-7}$ cm
Radioactive sources	α-particles	$\sim 10^{-12}$ cm
Accelerators	High energy electrons, protons	$\sim 10^{-16}$ cm

Units in particle physics

Energy

1 electron-Volt (eV):

the energy of a particle with electric charge = $|e|$, initially at rest, after acceleration by a difference of electrostatic potential = 1 Volt

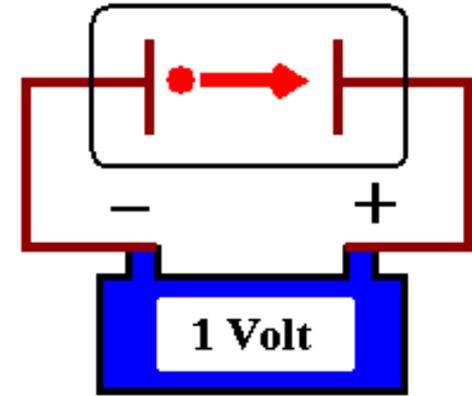
($e = 1.60 \times 10^{-19}$ C)

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

Multiples:

$$1 \text{ keV} = 10^3 \text{ eV} ; \quad 1 \text{ MeV} = 10^6 \text{ eV}$$

$$1 \text{ GeV} = 10^9 \text{ eV} ; \quad 1 \text{ TeV} = 10^{12} \text{ eV}$$



Energy of a proton in the LHC (in the year 2007):

$$7 \text{ TeV} = 1.12 \times 10^{-6} \text{ J}$$

(the same energy of a body of mass = 1 mg moving at speed = 1.5 m /s)

Energy and momentum for relativistic particles

(velocity v comparable to c)

Speed of light in vacuum $c = 2.99792 \times 10^8 \text{ m / s}$

Total energy: $E = mc^2 = \frac{m_0 c^2}{\sqrt{1 - (v/c)^2}}$ } (m : relativistic mass
 m_0 : rest mass)

Expansion in powers of (v/c) : $E = m_0 c^2 + \frac{1}{2} m_0 v^2 + \dots$

↑
energy
associated
with rest mass

↑
“classical”
kinetic
energy

Momentum: $p = mv = \frac{m_0 v}{\sqrt{1 - (v/c)^2}}$

$$\frac{pc}{E} = \frac{v}{c} \equiv \beta$$

$E^2 - p^2c^2 = (m_0c^2)^2$ “relativistic invariant”
(same value in all reference frames)

Special case: the photon ($v = c$ in vacuum)

$$\begin{array}{l} E = h \nu \\ \lambda = h / p \end{array} \quad \longrightarrow \quad \begin{array}{l} E / p = \nu \lambda = c \text{ (in vacuum)} \\ E^2 - p^2c^2 = 0 \\ \text{photon rest mass } m_\gamma = 0 \end{array}$$

Momentum units: eV/c (or MeV/c, GeV/c, ...)

Mass units: eV/c² (or MeV/c², GeV/c², ...)

Numerical example: electron with $v = 0.99 c$

Rest mass: $m_e = 0.511 \text{ MeV}/c^2$

$$\gamma \equiv \frac{1}{\sqrt{1 - (v/c)^2}} = 7.089 \quad (\text{often called “Lorentz factor”})$$

Total energy: $E = \gamma m_e c^2 = 7.089 \times 0.511 = 3.62 \text{ MeV}$

Momentum: $p = (v/c) \times (E/c) = 0.99 \times 3.62 = 3.58 \text{ MeV}/c$

First (wrong) ideas about nuclear structure (before 1932)

Observations

- Mass values of light nuclei \approx multiples of proton mass (to few %)
(proton \equiv nucleus of the hydrogen atom)
- β decay: spontaneous emission of electrons by some radioactive nuclei

Hypothesis: the atomic nucleus is a system of protons and electrons strongly bound together

**Nucleus of the atom with atomic number Z and mass number A :
a bound system of A protons and $(A - Z)$ electrons**

Total electric charge of the nucleus = $[A - (A - Z)]e = Z e$

Problem with this model: the “Nitrogen anomaly”

Spin of the Nitrogen nucleus = 1

Spin: intrinsic angular momentum of a particle (or system of particles)

In Quantum Mechanics only integer or half-integer multiples of $\hbar \equiv (h / 2\pi)$ are possible:

- integer values for orbital angular momentum (e.g., for the motion of atomic electrons around the nucleus)
- both integer and half-integer values for spin

Electron, proton spin = $\frac{1}{2}\hbar$ (measured)

Nitrogen nucleus ($A = 14, Z = 7$): 14 protons + 7 electrons = 21 spin $\frac{1}{2}$ particles

TOTAL SPIN MUST HAVE HALF-INTEGER VALUE

Measured spin = 1

DISCOVERY OF THE NEUTRON (Chadwick, 1932)



James Chadwick

**Neutron: a particle with mass \approx proton mass
but with zero electric charge**

Solution to the nuclear structure problem:

**Nucleus with atomic number Z and mass number A :
a bound system of Z protons and $(A - Z)$ neutrons**

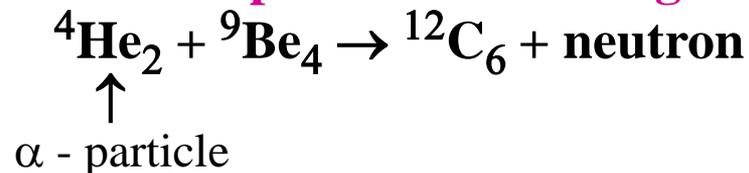
Nitrogen anomaly: no problem if neutron spin = $\frac{1}{2}\hbar$

Nitrogen nucleus ($A = 14, Z = 7$): 7 protons, 7 neutrons = 14 spin $\frac{1}{2}$ particles

\Rightarrow total spin has integer value

Neutron source in Chadwick's experiments: a ^{210}Po radioactive source

(5 MeV α - particles) mixed with Beryllium powder \Rightarrow emission of electrically neutral radiation capable of traversing several centimetres of Pb:



Basic principles of particle detection

Passage of charged particles through matter

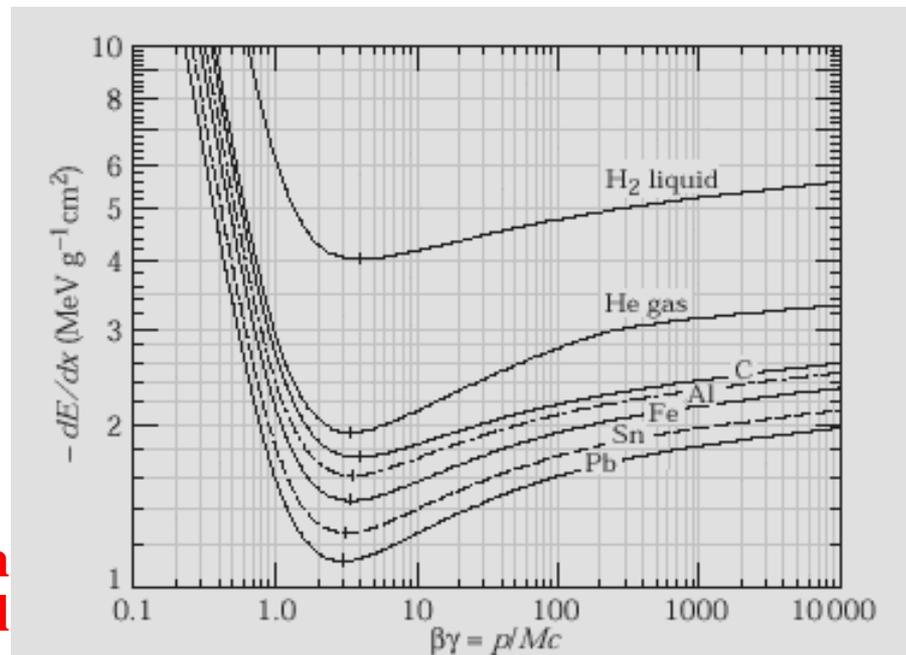
Interaction with atomic electrons \longrightarrow **ionization**
(neutral atom \rightarrow ion⁺ + free electron)

\longrightarrow **excitation of atomic energy levels**
(de-excitation \rightarrow photon emission)

Ionization + excitation of atomic energy levels \longrightarrow energy loss

Mean energy loss rate – dE/dx

- proportional to (electric charge)² of incident particle
- for a given material, function only of incident particle velocity
- typical value at minimum:
 $-dE/dx = 1 - 2 \text{ MeV}/(\text{g cm}^{-2})$



NOTE: traversed thickness (dx) is given in g/cm^2 to be independent of material density (for variable density materials, such as gases) – multiply dE/dx by density (g/cm^3) to obtain dE/dx in MeV/cm

Residual range

Residual range of a charged particle with initial energy E_0 losing energy only by ionization and atomic excitation:

$$R = \int_0^R dx = \int_{E_0}^{Mc^2} \frac{1}{dE/dx} dE = MF(v)$$

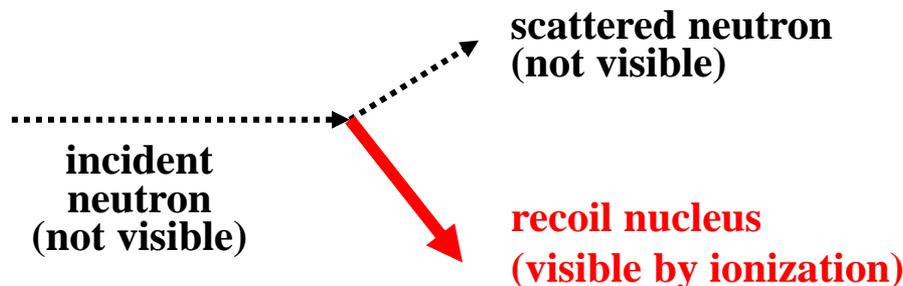
$\left(\begin{array}{l} M: \text{particle rest mass} \\ v: \text{initial velocity} \\ E_0 = Mc^2 / \sqrt{1 - (v/c)^2} \end{array} \right)$

⇒ the measurement of R for a particle of known rest mass M is a measurement of the initial velocity

**Passage of neutral particles through matter: no interaction with atomic electrons
⇒ detection possible only in case of collisions producing charged particles**

Neutron discovery:

observation and measurement of nuclear recoils in an “expansion chamber” filled with Nitrogen at atmospheric pressure



An old gaseous detector based on an expanding vapour; ionization acts as seed for the formation of liquid drops. Tracks can be photographed as strings of droplets

Incident neutron direction

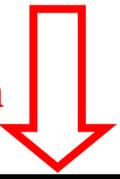
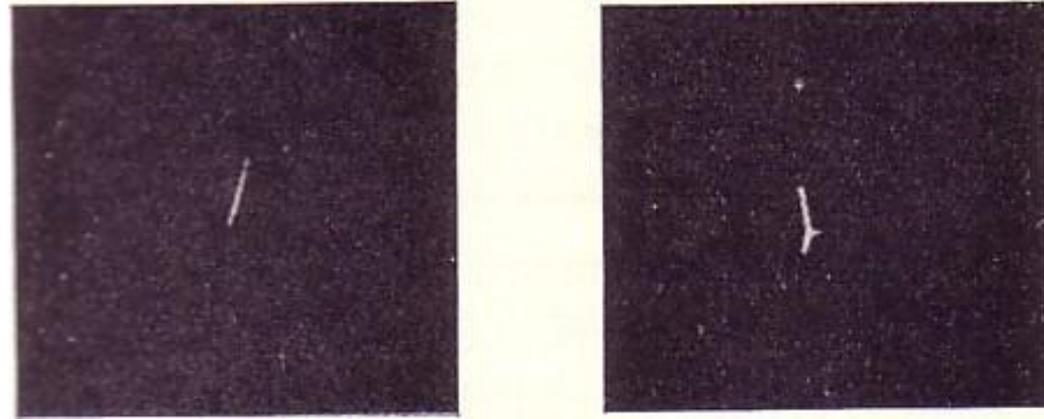


Plate containing free hydrogen (paraffin wax)

proton tracks ejected from paraffin wax



Recoiling Nitrogen nuclei

Assume that incident neutral radiation consists of particles of mass m moving with velocities $v < V_{\max}$

Determine max. velocity of recoil protons (U_p) and Nitrogen nuclei (U_N) from max. observed range

$$U_p = \frac{2m}{m + m_p} V_{\max}$$

$$U_N = \frac{2m}{m + m_N} V_{\max}$$

From non-relativistic energy-momentum conservation
 m_p : proton mass; m_N : Nitrogen nucleus mass

 $\frac{U_p}{U_N} = \frac{m + m_N}{m + m_p}$

From measured ratio U_p / U_N and known values of m_p, m_N determine neutron mass: $m \equiv m_n \approx m_p$

Present mass values : $m_p = 938.272 \text{ MeV}/c^2$; $m_n = 939.565 \text{ MeV}/c^2$

Pauli's exclusion principle

In Quantum Mechanics the electron orbits around the nucleus are “quantized”: **only some specific orbits (characterized by integer quantum numbers) are possible.**

Example: allowed orbit radii and energies for the Hydrogen atom

$$R_n = \frac{4\pi\epsilon_0\hbar^2 n^2}{me^2} \approx 0.53 \times 10^{-10} n^2 \text{ [m]}$$

$$E_n = -\frac{me^4}{2(4\pi\epsilon_0)^2\hbar^2 n^2} \approx -\frac{13.6}{n^2} \text{ [eV]}$$

$$\left(\begin{array}{l} m = m_e m_p / (m_e + m_p) \\ n = 1, 2, \dots \end{array} \right)$$

In atoms with $Z > 2$ only two electrons are found in the innermost orbit – WHY?

ANSWER (Pauli, 1925): two electrons (spin = 1/2) can never be in the same physical state

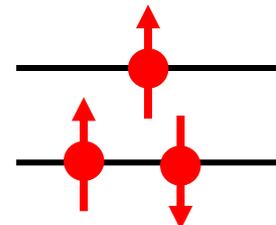
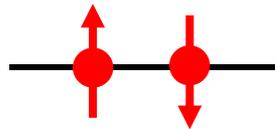
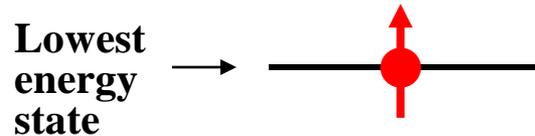


Wolfgang Pauli

Hydrogen ($Z = 1$)

Helium ($Z = 2$)

Lithium ($Z = 3$)



Pauli's exclusion principle applies to all particles with half-integer spin (collectively named Fermions)

ANTIMATTER

Discovered “theoretically” by P.A.M. Dirac (1928)

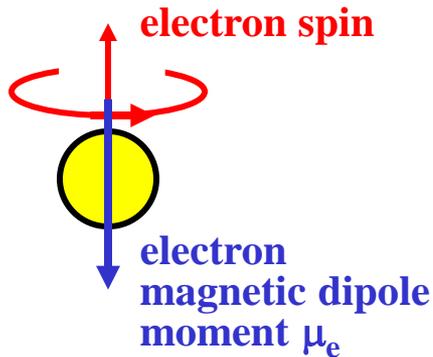


P.A.M. Dirac

Dirac's equation: a relativistic wave equation for the electron

Two surprising results:

- Motion of an electron in an electromagnetic field: presence of a term describing (for slow electrons) the potential energy of a magnetic dipole moment in a magnetic field
⇒ existence of an intrinsic electron magnetic dipole moment opposite to spin



$$\mu_e = \frac{e\hbar}{2m_e} \approx 5.79 \times 10^{-5} \text{ [eV/T]}$$

- For each solution of Dirac's equation with electron energy $E > 0$ there is another solution with $E < 0$

What is the physical meaning of these “negative energy” solutions ?

Generic solutions of Dirac's equation: complex wave functions $\Psi(\vec{r}, t)$

In the presence of an electromagnetic field, for each negative-energy solution the complex conjugate wave function Ψ^* is a positive-energy solution of Dirac's equation for an electron with opposite electric charge ($+e$)

Dirac's assumptions:

- nearly all electron negative-energy states are occupied and are not observable.
- electron transitions from a positive-energy to an occupied negative-energy state are forbidden by Pauli's exclusion principle.
- electron transitions from a positive-energy state to an empty negative-energy state are allowed \Rightarrow electron disappearance. To conserve electric charge, a positive electron (positron) must disappear $\Rightarrow e^+e^-$ annihilation.
- electron transitions from a negative-energy state to an empty positive-energy state are also allowed \Rightarrow electron appearance. To conserve electric charge, a positron must appear \Rightarrow creation of an e^+e^- pair.

\Rightarrow empty electron negative-energy states describe positive energy states of the positron

Dirac's perfect vacuum: a region where all positive-energy states are empty and all negative-energy states are full.

Positron magnetic dipole moment = μ_e but oriented parallel to positron spin

Experimental confirmation of antimatter

(C.D. Anderson, 1932)

Detector: a Wilson cloud – chamber (visual detector based on a gas volume containing vapour close to saturation) in a magnetic field, exposed to cosmic rays



Carl D. Anderson

Measure particle momentum and sign of electric charge from magnetic curvature

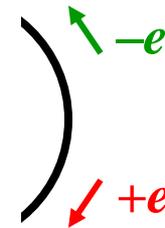
Lorentz force $\vec{f} = e\vec{v} \times \vec{B}$ **→ projection of the particle trajectory in a plane perpendicular to \vec{B} is a circle**

Circle radius for electric charge $|e|$:
$$R [\text{m}] = \frac{10 p_{\perp} [\text{GeV}/c]}{3B [\text{T}]}$$

p_{\perp} : momentum component perpendicular to magnetic field direction

NOTE: impossible to distinguish between positively and negatively charged particles going in opposite directions

⇒ need an independent determination of the particle direction of motion

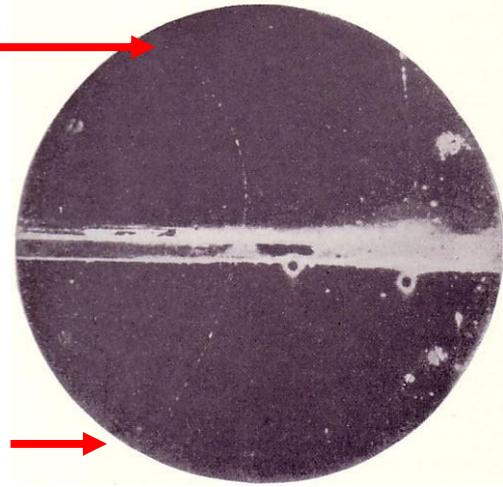


First experimental observation of a positron

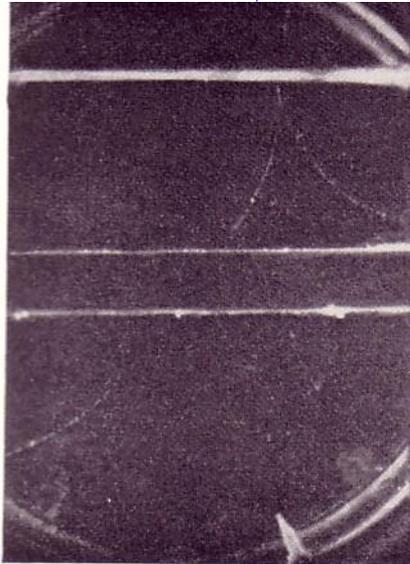
23 MeV positron

6 mm thick Pb plate

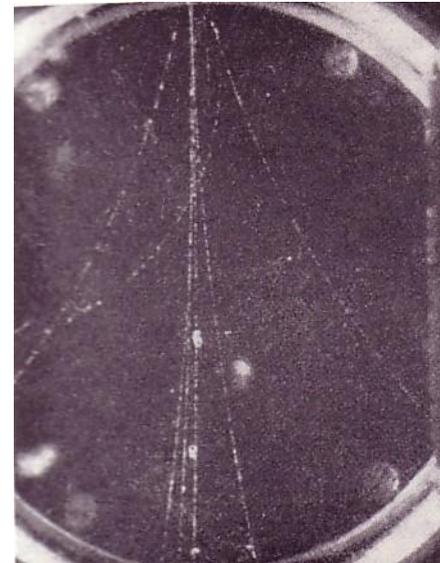
63 MeV positron



direction of high-energy photon



Production of an electron-positron pair by a high-energy photon in a Pb plate

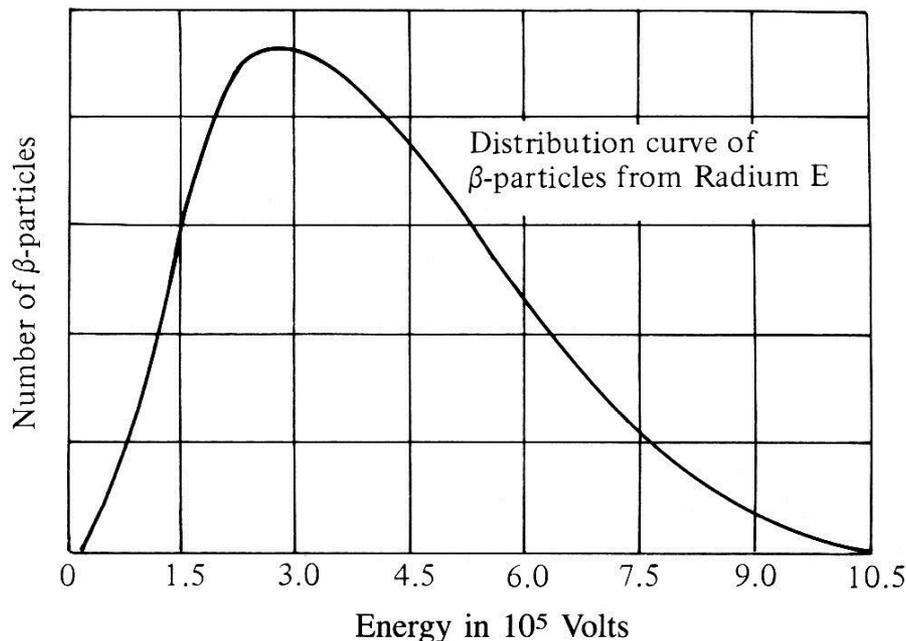


Cosmic-ray "shower" containing several $e^+ e^-$ pairs

Neutrinos

A puzzle in β – decay: the continuous electron energy spectrum

First measurement by Chadwick (1914)



Radium E: $^{210}\text{Bi}_{83}$
(a radioactive isotope
produced in the decay chain
of ^{238}U)

If β – decay is $(A, Z) \rightarrow (A, Z+1) + e^-$, then the emitted electron is mono-energetic:

$$\text{electron total energy } E = [M(A, Z) - M(A, Z+1)]c^2$$

(neglecting the kinetic energy of the recoil nucleus $\frac{1}{2}p^2/M(A, Z+1) \ll E$)

Several solutions to the puzzle proposed before the 1930's (all wrong), including violation of energy conservation in β – decay

December 1930: public letter sent by W. Pauli to a physics meeting in Tübingen

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

...because of the “wrong” statistics of the N and ${}^6\text{Li}$ nuclei and the continuous β -spectrum,

I have hit upon a desperate remedy to save the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin $\frac{1}{2}$ and obey the exclusion principle The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous β -spectrum would then become understandable by the assumption that in β -decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant.

..... For the moment, however, I do not dare to publish anything on this idea

So, dear Radioactives, examine and judge it. Unfortunately I cannot appear in Tübingen personally, since I am indispensable here in Zürich because of a ball on the night of 6/7 December.

W. Pauli

NOTES

- Pauli's neutron is a light particle \Rightarrow not the neutron that will be discovered by Chadwick one year later
- As everybody else at that time, Pauli believed that if radioactive nuclei emit particles, these particles must exist in the nuclei before emission

Theory of β -decay (E. Fermi, 1932-33)

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

β^+ decay: $p \rightarrow n + e^+ + \nu$ (e.g., $^{14}\text{O}_8 \rightarrow ^{14}\text{N}_7 + e^+ + \nu$)

ν : the particle proposed by Pauli
(named “neutrino” by Fermi)

$\bar{\nu}$: its antiparticle (antineutrino)



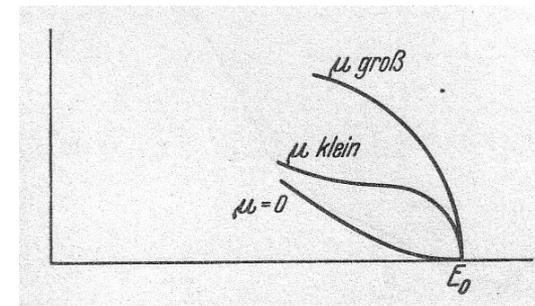
Enrico Fermi

Fermi's theory: a point interaction among four spin $1/2$ particles, using the mathematical formalism of creation and annihilation operators invented by Jordan
 \Rightarrow particles emitted in β – decay need not exist before emission – they are “created” at the instant of decay

Prediction of β – decay rates and electron energy spectra as a function of only one parameter: Fermi coupling constant G_F (determined from experiments)

Energy spectrum dependence on neutrino mass μ
(from Fermi's original article, published in German on *Zeitschrift für Physik*, following rejection of the English version by *Nature*)

Measurable distortions for $\mu > 0$ near the end-point (E_0 : max. allowed electron energy)



Neutrino detection

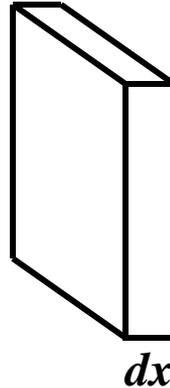
Prediction of Fermi's theory: $\bar{\nu} + p \rightarrow e^+ + n$

$\bar{\nu} - p$ interaction probability in thickness dx of hydrogen-rich material (e.g., H_2O)

Incident $\bar{\nu}$:

Flux Φ [$\bar{\nu} \text{ cm}^{-2} \text{ s}^{-1}$]

(uniform over surface S)



Target:

surface S , thickness dx

containing n protons cm^{-3}

$\bar{\nu} p$ interaction rate = $\Phi S n \sigma dx$ interactions per second

σ : $\bar{\nu} - p$ cross-section (effective proton area, as seen by the incident $\bar{\nu}$)

$\bar{\nu} p$ interaction probability = $n \sigma dx = dx / \lambda$

Interaction mean free path: $\lambda = 1 / n \sigma$

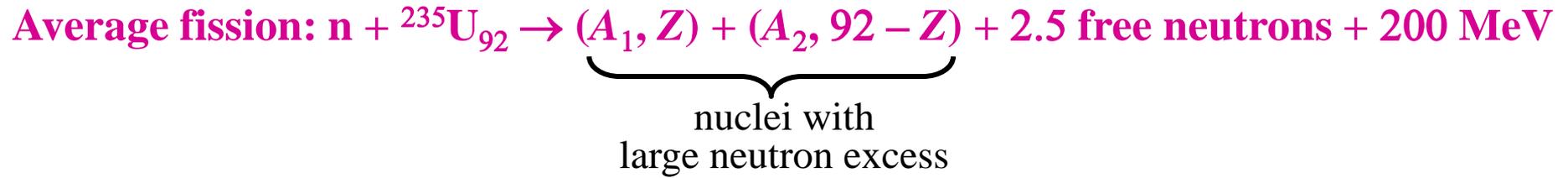
Interaction probability for finite target thickness $T = 1 - \exp(-T / \lambda)$

$\sigma(\bar{\nu} p) \approx 10^{-43} \text{ cm}^2$ for 3 MeV $\bar{\nu} \Rightarrow \lambda \approx 150$ light-years of water !

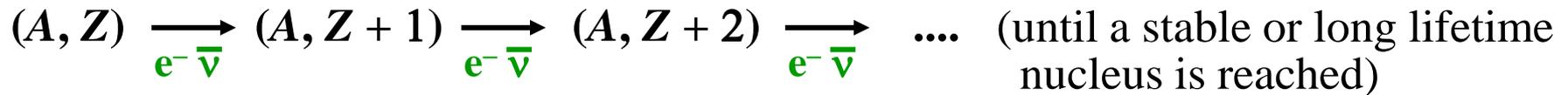
Interaction probability $\approx T / \lambda$ very small ($\sim 10^{-18}$ per metre H_2O)

\Rightarrow need very intense sources for antineutrino detection

Nuclear reactors: very intense antineutrino sources



→ a chain of β decays with very short lifetimes:



On average, 6 $\bar{\nu}$ per fission

$$\bar{\nu} \text{ production rate} = \frac{6P_t}{200 \text{ MeV} \times \underbrace{1.6 \times 10^{-13}}_{\substack{\text{conversion factor} \\ \text{MeV} \rightarrow \text{J}}}} = 1.87 \times 10^{11} P_t \bar{\nu}/\text{s}$$

P_t : reactor thermal power [W]

For a typical reactor: $P_t = 3 \times 10^9 \text{ W} \Rightarrow 5.6 \times 10^{20} \bar{\nu} / \text{s}$ (isotropic)

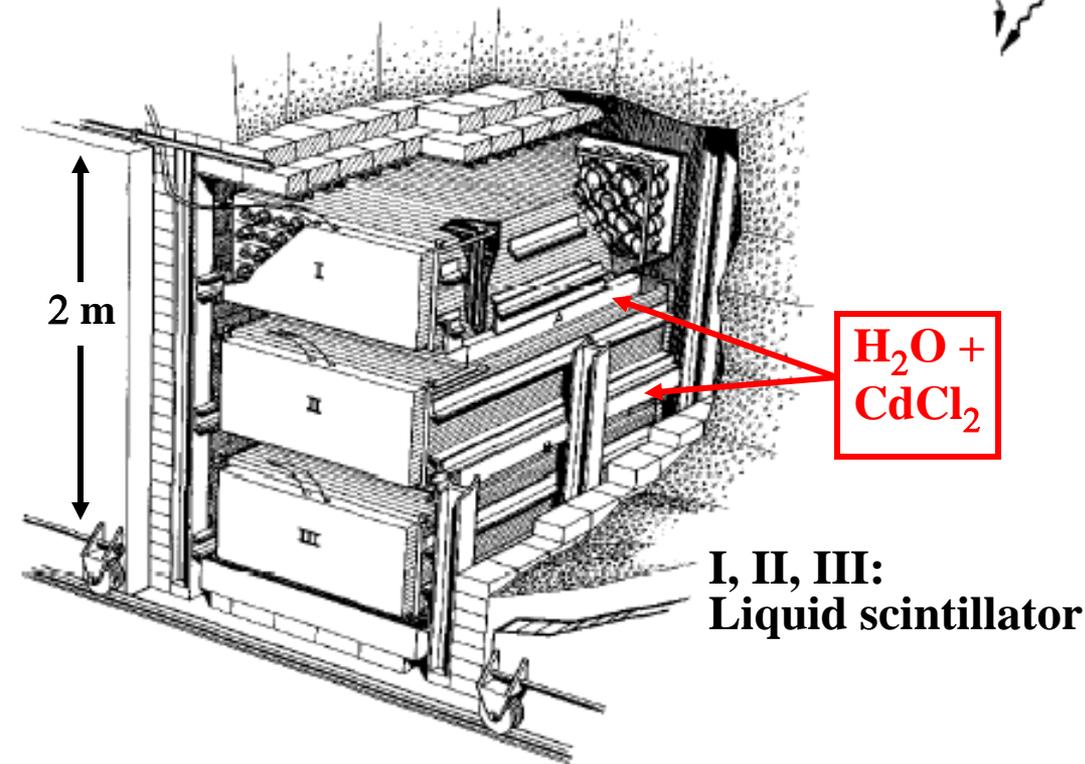
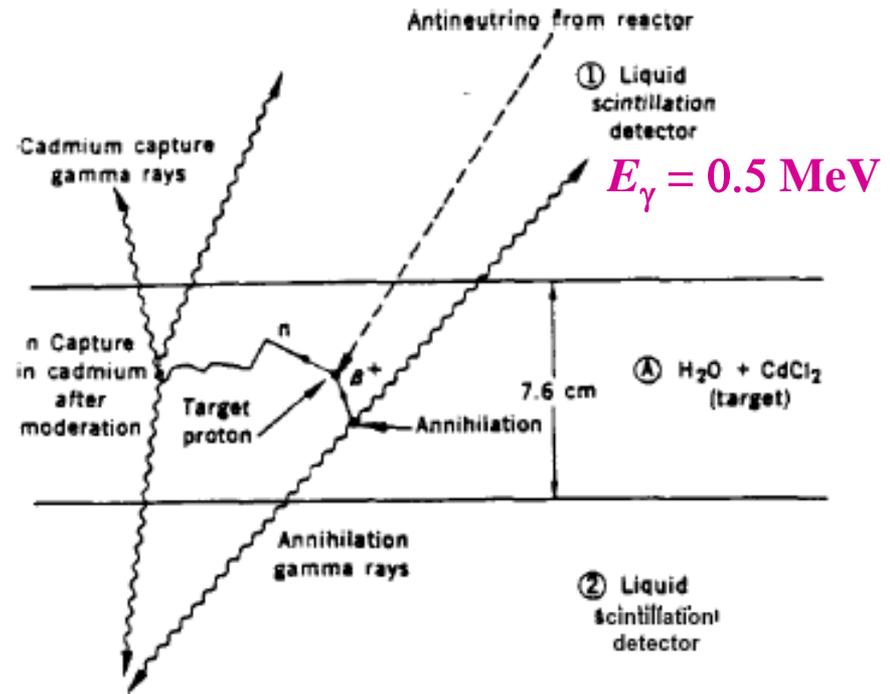
Continuous $\bar{\nu}$ energy spectrum – average energy $\sim 3 \text{ MeV}$

First neutrino detection

(Reines, Cowan 1953)



- detect 0.5 MeV γ -rays from $e^+e^- \rightarrow \gamma\gamma$ ($t = 0$)
- neutron “thermalization” followed by capture in Cd nuclei \Rightarrow emission of delayed γ -rays (average delay $\sim 30 \mu\text{s}$)



Event rate at the Savannah River nuclear power plant:

3.0 ± 0.2 events / hour

(after subtracting event rate measured with reactor OFF)

in agreement with expectations

COSMIC RAYS

- Discovered by V.F. Hess in the 1910's by the observation of the increase of radioactivity with altitude during a balloon flight
- Until the late 1940's, the only existing source of high-energy particles

Composition of cosmic rays at sea level – two main components

- Electromagnetic “showers”, consisting of many e^\pm and γ -rays, mainly originating from:

$\gamma + \text{nucleus} \rightarrow e^+e^- + \text{nucleus}$ (pair production);

$e^\pm + \text{nucleus} \rightarrow e^\pm + \gamma + \text{nucleus}$ (“bremsstrahlung”)

The typical mean free path for these processes (“radiation length”, x_0) depends on Z .

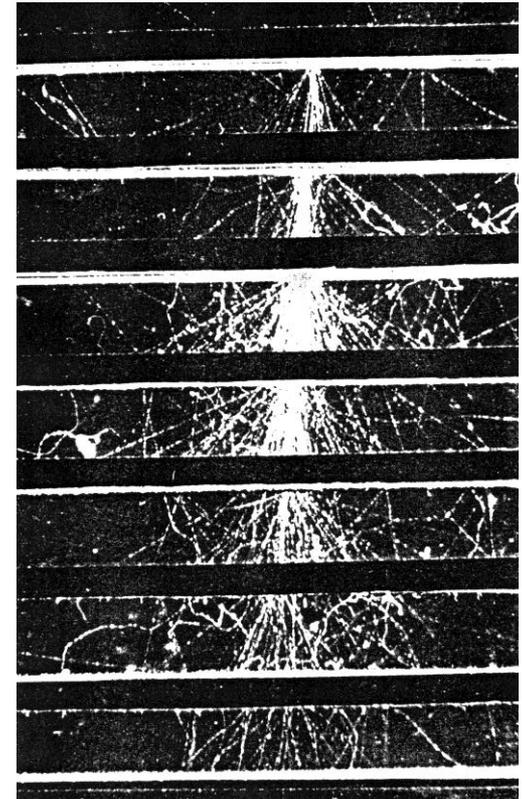
For Pb ($Z = 82$) $x_0 = 0.56$ cm

Thickness of the atmosphere $\approx 27 x_0$

- Muons (μ^\pm) capable of traversing as much as 1 m of Pb without interacting; tracks observed in cloud chambers in the 1930's.

Determination of the mass by simultaneous measurement of momentum $p = mv(1 - v^2/c^2)^{-1/2}$ (track curvature in magnetic field) and velocity v (ionization):

$$m_\mu = 105.66 \text{ MeV}/c^2 \approx 207 m_e$$

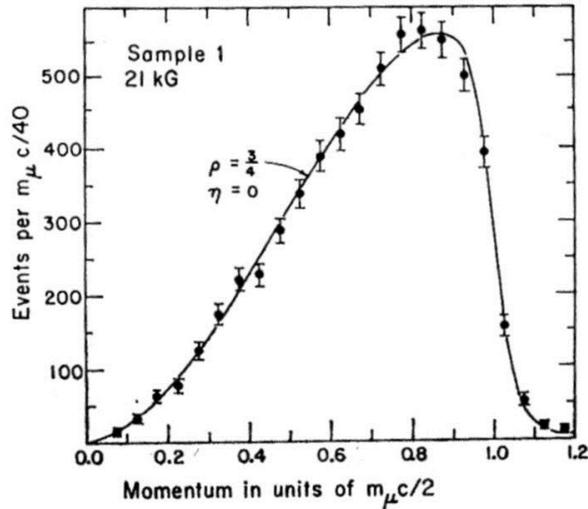


Cloud chamber image of an electromagnetic shower.
Pb plates, each 1.27 cm thick

Muon decay

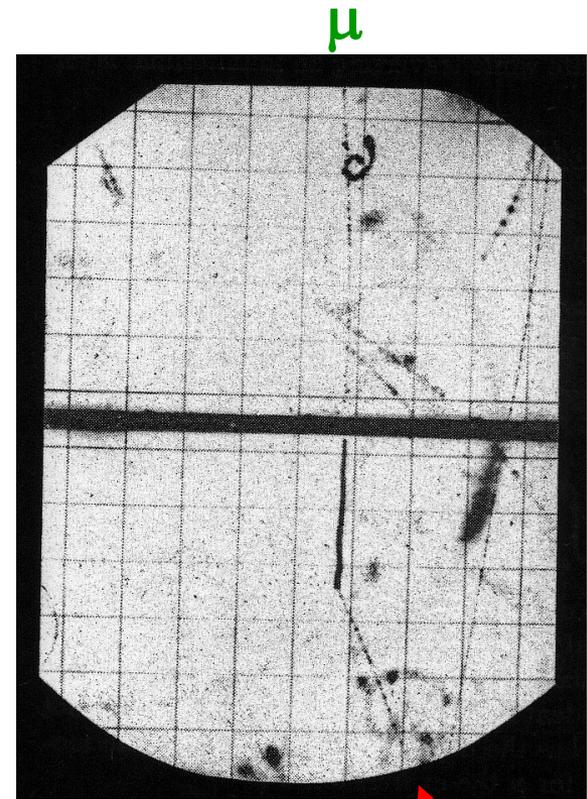


Decay electron momentum distribution



Cosmic ray muon stopping in a cloud chamber and decaying to an electron

Muon spin = $\frac{1}{2}$



decay electron track

Muon lifetime at rest: $\tau_\mu = 2.197 \times 10^{-6} \text{ s} \equiv 2.197 \mu\text{s}$

Muon decay mean free path in flight:

$$\lambda_{decay} = \frac{v \tau_\mu}{\sqrt{1-(v/c)^2}} = \frac{p \tau_\mu}{m_\mu} = \frac{p}{m_\mu c} \tau_\mu c$$

$\left(\begin{array}{l} p : \text{muon momentum} \\ \tau_\mu c \approx 0.66 \text{ km} \end{array} \right)$

\Rightarrow muons can reach the Earth surface after a path $\geq 10 \text{ km}$ because the decay mean free path is stretched by the relativistic time expansion

Particle interactions (as known until the mid 1960's)

In order of increasing strength:

- **Gravitational interaction (all particles)**

Totally negligible in particle physics

Example: static force between electron and proton at distance D

$$\text{Gravitational: } f_G = G_N \frac{m_e m_p}{D^2} \qquad \text{Electrostatic: } f_E = \frac{1}{4\pi\epsilon_0} \frac{e^2}{D^2}$$

$$\text{Ratio } f_G / f_E \approx 4.4 \times 10^{-40}$$

- **Weak interaction (all particles except photons)**

Responsible for β decay and for slow nuclear fusion reactions in the star core

Example: in the core of the Sun ($T = 15.6 \times 10^6$ °K) $4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu$

Solar neutrino emission rate $\sim 1.84 \times 10^{38}$ neutrinos / s

Flux of solar neutrinos on Earth $\sim 6.4 \times 10^{10}$ neutrinos $\text{cm}^{-2} \text{ s}^{-1}$

Very small interaction radius R_{int} (max. distance at which two particles interact)
($R_{\text{int}} = 0$ in the original formulation of Fermi's theory)

- **Electromagnetic interaction (all charged particles)**

Responsible for chemical reactions, light emission from atoms, etc.

Infinite interaction radius

(example: the interaction between electrons in transmitting and receiving antennas)

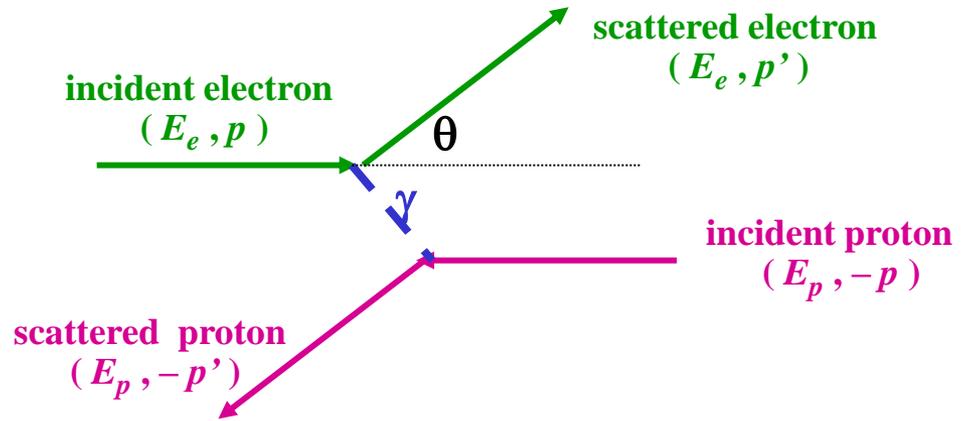
- **Strong interaction** (neutron, proton, ... **NOT THE ELECTRON !**)
 Responsible for keeping protons and neutrons together in the atomic nucleus
 Independent of electric charge
Interaction radius $R_{\text{int}} \approx 10^{-13}$ cm

**In Relativistic Quantum Mechanics static fields of forces DO NOT EXIST ;
 the interaction between two particles is “transmitted” by intermediate particles
 acting as “interaction carriers”**

**Example: electron – proton scattering (an effect of the electromagnetic interaction)
 is described as a two-step process :** 1) incident electron \rightarrow scattered electron + photon
 2) photon + incident proton \rightarrow scattered proton

The photon (γ) is the carrier of the electromagnetic interaction

**In the electron – proton
 centre-of-mass system**



Energy – momentum conservation:

$$E_\gamma = 0$$

$$\vec{p}_\gamma = \vec{p} - \vec{p}' \quad (|\vec{p}| = |\vec{p}'|)$$

“Mass” of the intermediate photon: $Q^2 \equiv E_\gamma^2 - p_\gamma^2 c^2 = - 2 p^2 c^2 (1 - \cos \theta)$

**The photon is in a VIRTUAL state because for real photons $E_\gamma^2 - p_\gamma^2 c^2 = 0$
 (the mass of real photons is ZERO) – virtual photons can only travel over
 very short distances thanks to the “Uncertainty Principle”**

The Uncertainty Principle

CLASSICAL MECHANICS

Position and momentum of a particle can be measured independently and simultaneously with arbitrary precision



Werner Heisenberg

QUANTUM MECHANICS

Measurement perturbs the particle state \Rightarrow position and momentum measurements are correlated:

$$\Delta x \Delta p_x \approx \hbar$$

(also for y and z components)

Numerical example:

$$\Delta p_x = 100 \text{ MeV}/c \quad \Longrightarrow \quad \Delta x \approx 1.97 \times 10^{-13} \text{ cm}$$

1937: Theory of nuclear forces (H. Yukawa)

Existence of a new light particle (“meson”)
as the carrier of nuclear forces

Relation between interaction radius and meson mass m :

$$R_{\text{int}} = \frac{\hbar}{mc} \quad \longrightarrow \quad mc^2 \approx 200 \text{ MeV} \\ \text{for } R_{\text{int}} \approx 10^{-13} \text{ cm}$$



Hideki Yukawa

Yukawa’s meson initially identified with the muon – in this case μ^- stopping in matter should be immediately absorbed by nuclei \Rightarrow nuclear breakup (not true for stopping μ^+ because of Coulomb repulsion - μ^+ never come close enough to nuclei, while μ^- form “muonic” atoms)

Experiment of Conversi, Pancini, Piccioni (Rome, 1945):
study of μ^- stopping in matter using μ^- magnetic selection in the cosmic rays

In light material ($Z \leq 10$) the μ^- decays mainly to electron (just as μ^+)
In heavier material, the μ^- disappears partly by decaying to electron, and partly by nuclear capture (process later understood as $\mu^- + p \rightarrow n + \nu$).
However, the rate of nuclear captures is consistent with the weak interaction.



the muon is not Yukawa’s meson

1947: Discovery of the π - meson (the “real” Yukawa particle)

Observation of the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain in nuclear emulsion exposed to cosmic rays at high altitudes

Nuclear emulsion: a detector sensitive to ionization with $\sim 1 \mu\text{m}$ space resolution (AgBr microcrystals suspended in gelatin)

In all events the muon has a fixed kinetic energy (4.1 MeV, corresponding to a range of $\sim 600 \mu\text{m}$ in nuclear emulsion) \Rightarrow two-body decay

$m_\pi = 139.57 \text{ MeV}/c^2$; spin = 0

Dominant decay mode: $\pi^+ \rightarrow \mu^+ + \nu$
(and $\pi^- \rightarrow \mu^- + \bar{\nu}$)

Mean life at rest: $\tau_\pi = 2.6 \times 10^{-8} \text{ s} = 26 \text{ ns}$

π^- at rest undergoes nuclear capture, as expected for the Yukawa particle

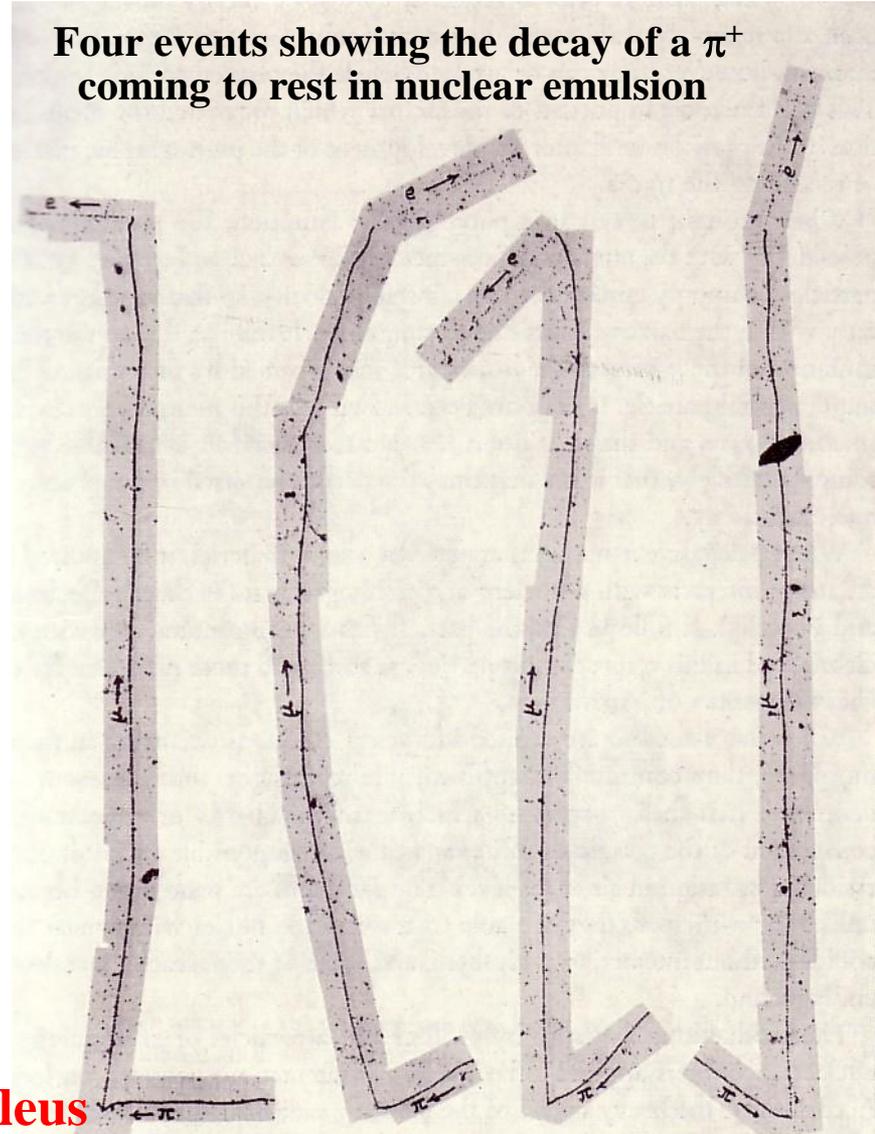
A neutral π - meson (π^0) also exists:

$m(\pi^0) = 134.98 \text{ MeV}/c^2$

Decay: $\pi^0 \rightarrow \gamma + \gamma$, mean life = $8.4 \times 10^{-17} \text{ s}$

π - mesons are the most copiously produced particles in proton - proton and proton - nucleus collisions at high energies

Four events showing the decay of a π^+ coming to rest in nuclear emulsion



CONSERVED QUANTUM NUMBERS

Why is the free proton stable?

Possible proton decay modes (allowed by all known conservation laws: energy – momentum, electric charge, angular momentum):

$$p \rightarrow \pi^0 + e^+$$

$$p \rightarrow \pi^0 + \mu^+$$

$$p \rightarrow \pi^+ + \nu$$

.....

No proton decay ever observed – the proton is STABLE

Limit on the proton mean life: $\tau_p > 1.6 \times 10^{25}$ years

Invent a new quantum number : “Baryonic Number” B

B = 1 for proton, neutron

B = -1 for antiproton, antineutron

B = 0 for e^\pm , μ^\pm , neutrinos, mesons, photons

Require conservation of baryonic number in all particle processes:

$$\sum_i B_i = \sum_f B_f$$

(*i* : initial state particle ; *f* : final state particle)

Strangeness

Late 1940's: discovery of a variety of heavier mesons (K – mesons) and baryons (“hyperons”) – studied in detail in the 1950's at the new high-energy proton synchrotrons (the 3 GeV “cosmotron” at the Brookhaven National Lab and the 6 GeV Bevatron at Berkeley)

Mass values

Mesons (spin = 0): $m(K^\pm) = 493.68 \text{ MeV}/c^2$; $m(K^0) = 497.67 \text{ MeV}/c^2$

Hyperons (spin = 1/2): $m(\Lambda) = 1115.7 \text{ MeV}/c^2$; $m(\Sigma^\pm) = 1189.4 \text{ MeV}/c^2$

$m(\Xi^0) = 1314.8 \text{ MeV}/c^2$; $m(\Xi^-) = 1321.3 \text{ MeV}/c^2$

Properties

- Abundant production in proton – nucleus , π – nucleus collisions
- Production cross-section typical of strong interactions ($\sigma > 10^{-27} \text{ cm}^2$)
- Production in pairs (example: $\pi^- + p \rightarrow K^0 + \Lambda$; $K^- + p \rightarrow \Xi^- + K^+$)
- Decaying to lighter particles with mean life values $10^{-8} - 10^{-10} \text{ s}$ (as expected for a weak decay)

Examples of decay modes

$K^\pm \rightarrow \pi^\pm \pi^0$; $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$; $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$; $K^0 \rightarrow \pi^+ \pi^-$; $K^0 \rightarrow \pi^0 \pi^0$; ...

$\Lambda \rightarrow p \pi^-$; $\Lambda \rightarrow n \pi^0$; $\Sigma^+ \rightarrow p \pi^0$; $\Sigma^+ \rightarrow n \pi^+$; $\Sigma^+ \rightarrow n \pi^-$; ...

$\Xi^- \rightarrow \Lambda \pi^-$; $\Xi^0 \rightarrow \Lambda \pi^0$

Antiproton discovery (1955)

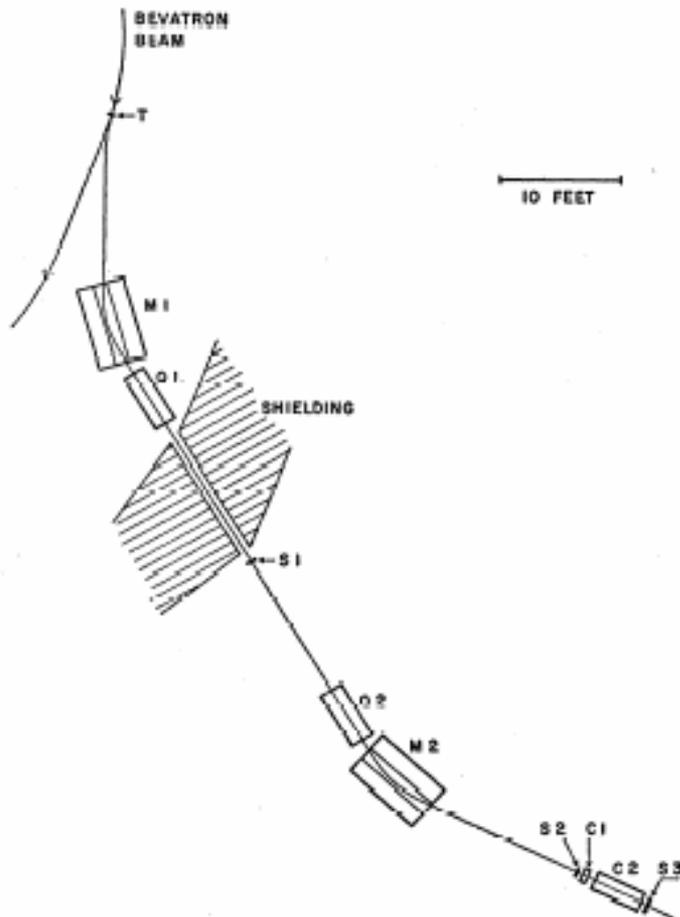
Threshold energy for antiproton (\bar{p}) production in proton – proton collisions

Baryon number conservation \Rightarrow simultaneous production of \bar{p} and p (or \bar{p} and n)

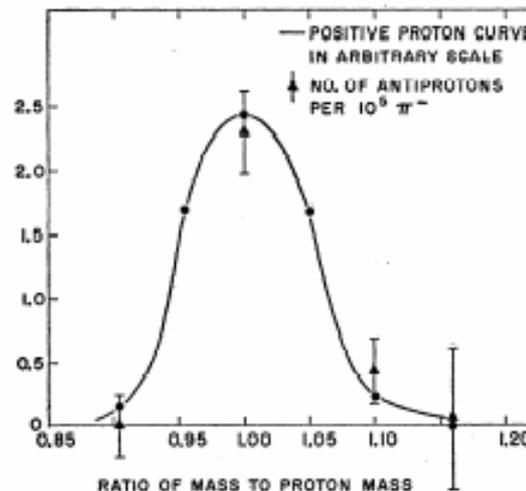
Example: $p + p \rightarrow p + p + \bar{p} + p$

Threshold energy ~ 6 GeV

**“Bevatron”: 6 GeV
proton synchrotron in Berkeley**

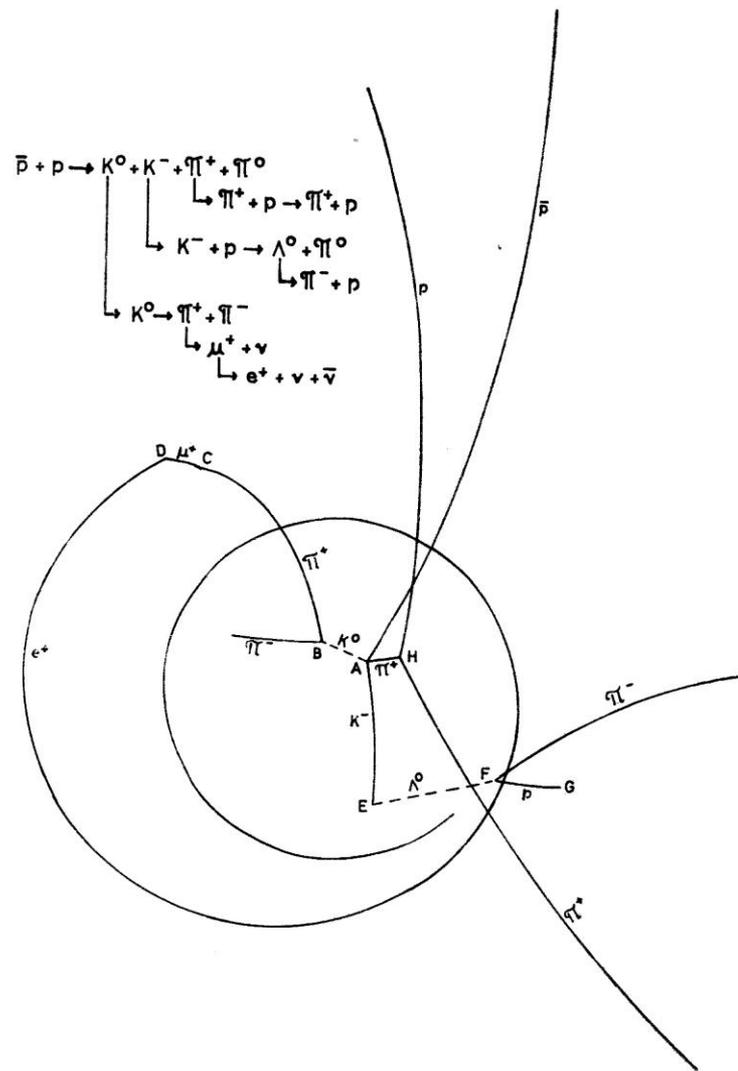


- build a beam line for 1.19 GeV/c momentum
- select negatively charged particles (mostly π^-)
- reject fast π^- by Čerenkov effect: light emission in transparent medium if particle velocity $v > c/n$ (n : refraction index) – antiprotons have $v < c/n \Rightarrow$ no Čerenkov light
- measure time of flight between counters S_1 and S_2 (12 m path): 40 ns for π^- , 51 ns for antiprotons



**For fixed momentum,
time of flight gives
particle velocity, hence
particle mass**

Example of antiproton annihilation at rest in a liquid hydrogen bubble chamber



Another neutrino

A puzzle of the late 1950's: the absence of $\mu \rightarrow e \gamma$ decays

Experimental limit: < 1 in 10^6 $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ decays

A possible solution: existence of a new, conserved “muonic” quantum number distinguishing muons from electrons

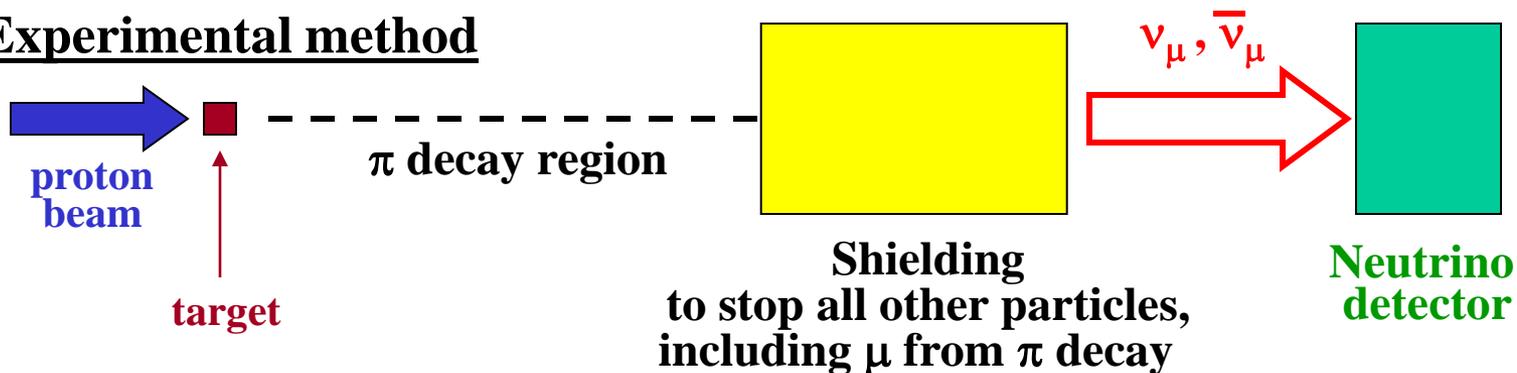
To allow $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ decays, $\bar{\nu}$ must have “muonic” quantum number but not $\nu \Rightarrow$ in μ^+ decay the $\bar{\nu}$ is not the antiparticle of ν

\Rightarrow two distinct neutrinos (ν_e, ν_μ) in the decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

Consequence for π – meson decays: $\pi^+ \rightarrow \mu^+ \nu_\mu$; $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ to conserve the “muonic” quantum number

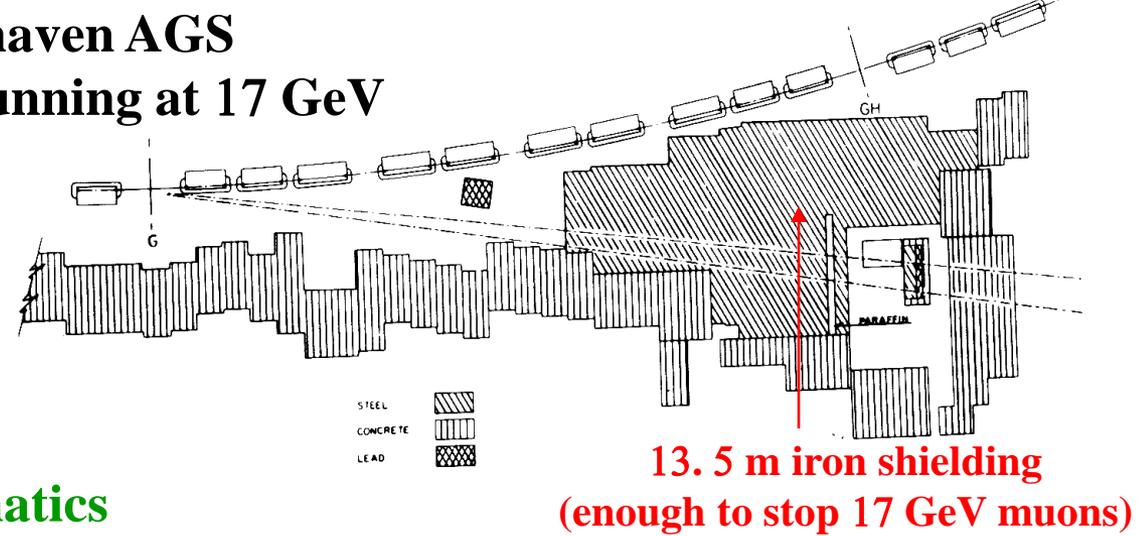
High energy proton accelerators: intense sources of π^\pm – mesons $\Rightarrow \nu_\mu, \bar{\nu}_\mu$

Experimental method



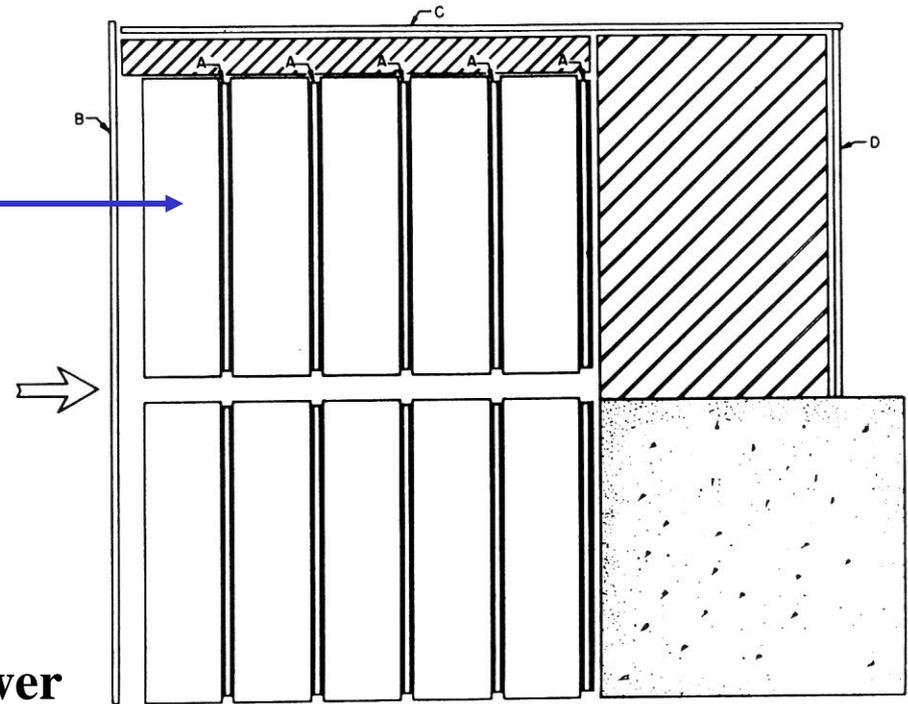
If $\nu_\mu \neq \nu_e$, ν_μ interactions produce μ^- and not e^- (example: $\nu_\mu + n \rightarrow \mu^- + p$)

1962: ν_μ discovery at the Brookhaven AGS
(a 30 GeV proton synchrotron running at 17 GeV
for the neutrino experiment)



Neutrino energy spectrum
known from π , K production
and $\pi \rightarrow \mu$, $K \rightarrow \mu$ decay kinematics

Spark chamber
each with 9 Al plates
(112 x 112 x 2.5 cm)
mass 1 Ton



Muon – electron separation

Muon: long track

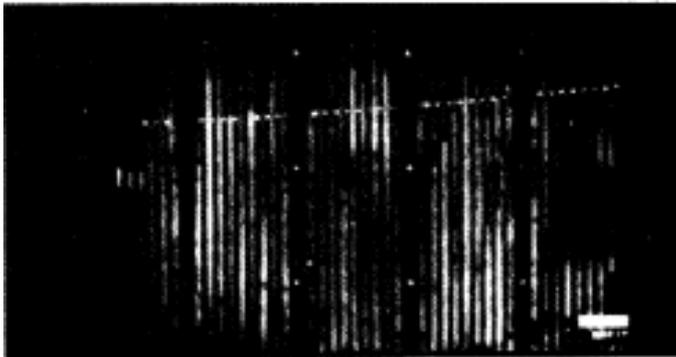
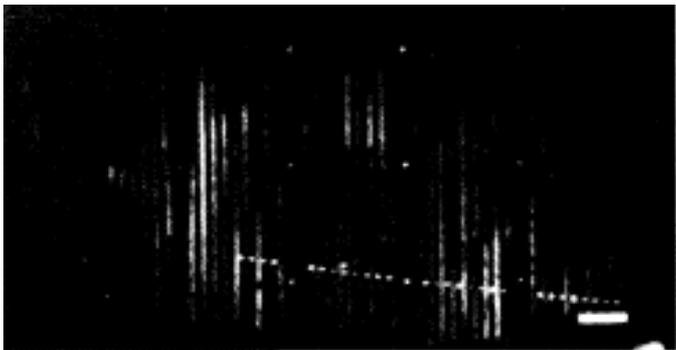
Electron: short, multi-spark event
from electromagnetic shower

Neutrino detector

64 “events” from a 300 hour run:

- 34 single track events, consistent with μ track
- 2 events consistent with electron shower
(from small, calculable ν_e contamination in beam)

Clear demonstration that $\nu_\mu \neq \nu_e$



Three typical single-track events in the BNL neutrino experiment

THE “STATIC” QUARK MODEL

Late 1950’s – early 1960’s: discovery of many strongly interacting particles at the high energy proton accelerators (Berkeley Bevatron, BNL AGS, CERN PS), all with very short mean life times ($10^{-20} - 10^{-23}$ s, typical of strong decays)
⇒ catalog of **> 100 strongly interacting particles (collectively named “hadrons”)**

ARE HADRONS ELEMENTARY PARTICLES?

1964 (Gell-Mann, Zweig): Hadron classification into “families”; observation that all hadrons could be built from three spin $1/2$ “building blocks” (named “quarks” by Gell-Mann):

	<i>u</i>	<i>d</i>	<i>s</i>
Electric charge (units $ e $)	+2/3	-1/3	-1/3
Baryonic number	1/3	1/3	1/3
Strangeness	0	0	-1

and three antiquarks (\bar{u} , \bar{d} , \bar{s}) with opposite electric charge and opposite baryonic number and strangeness

Mesons: quark – antiquark pairs

Examples of non-strange mesons:

$$\pi^+ \equiv u\bar{d} \quad ; \quad \pi^- \equiv \bar{u}d \quad ; \quad \pi^0 \equiv (d\bar{d} - u\bar{u})/\sqrt{2}$$

Examples of strange mesons:

$$K^- \equiv s\bar{u} \quad ; \quad \bar{K}^0 \equiv s\bar{d} \quad ; \quad K^+ \equiv \bar{s}u \quad ; \quad K^0 \equiv \bar{s}d$$

Baryons: three quarks bound together

Antibaryons: three antiquarks bound together

Examples of non-strange baryons:

$$\text{proton} \equiv uud \quad ; \quad \text{neutron} \equiv udd$$

Examples of strangeness -1 baryons:

$$\Sigma^+ \equiv suu \quad ; \quad \Sigma^0 \equiv sud \quad ; \quad \Sigma^- \equiv sdd$$

Examples of strangeness -2 baryons:

$$\Xi^0 \equiv ssu \quad ; \quad \Xi^- \equiv ssd$$

Prediction and discovery of the Ω^- particle

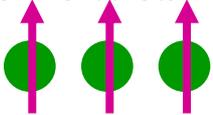
A success of the static quark model

The “decuplet” of spin $\frac{3}{2}$ baryons

Strangeness

Mass (MeV/c²)

0	N^{*++} <i>uuu</i>	N^{*+} <i>uud</i>	$N^{*\circ}$ <i>udd</i>	N^{*-} <i>ddd</i>	1232
-1	Σ^{*+} <i>suu</i>	$\Sigma^{*\circ}$ <i>sud</i>	Σ^{*-} <i>sdd</i>		1384
-2		$\Xi^{*\circ}$ <i>ssu</i>	Ξ^{*-} <i>ssd</i>		1533
-3			Ω^- <i>sss</i>		1672 (predicted)

Ω^- : the bound state of three *s* – quarks with the lowest mass
with total angular momentum = 3/2 \Rightarrow 

Pauli’s exclusion principle requires that the three quarks cannot be identical

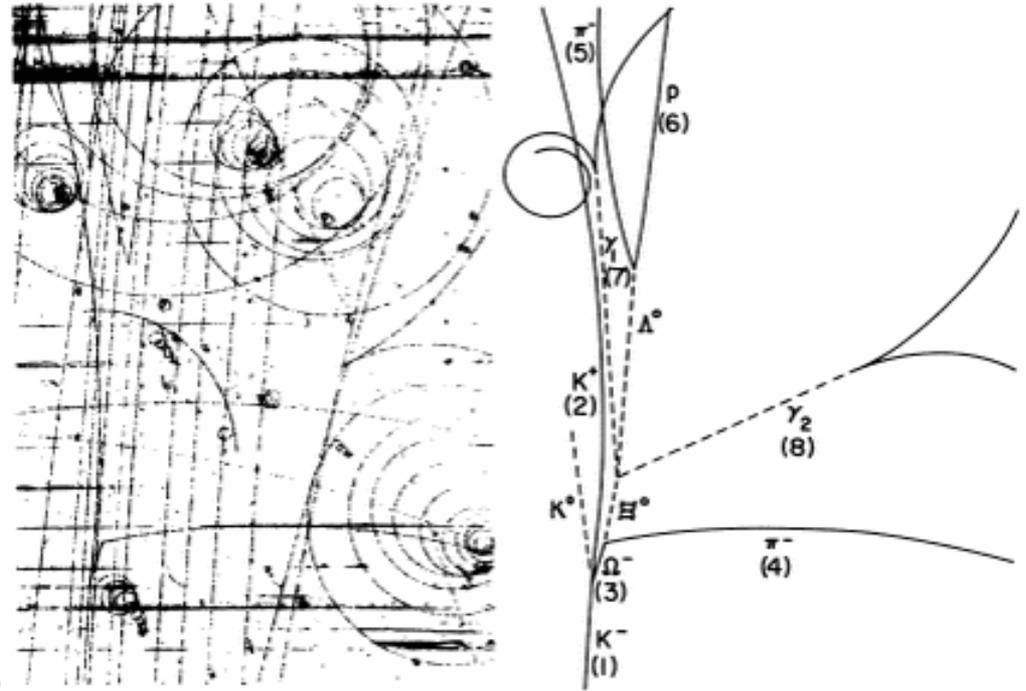
The first Ω^- event (observed in the 2 m liquid hydrogen bubble chamber at BNL using a 5 GeV/c K^- beam from the 30 GeV AGS)

Chain of events in the picture:



with both γ -rays converting to an e^+e^- in liquid hydrogen

(very lucky event, because the mean free path for $\gamma \rightarrow e^+e^-$ in liquid hydrogen is ~ 10 m)



Ω^- mass measured from this event = $1686 \pm 12 \text{ MeV}/c^2$



The Stanford two-mile electron linear accelerator (SLAC)

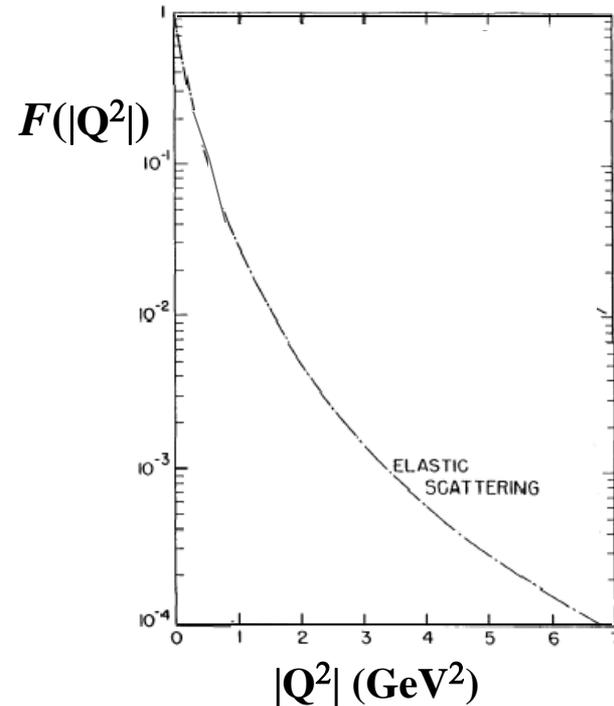
**Electron elastic scattering from a point-like charge $|e|$ at high energies:
differential cross-section in the collision centre-of-mass (Mott's formula)**

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 (\hbar c)^2 \cos^2(\theta/2)}{8E^2 \sin^4(\theta/2)} \equiv \sigma_M \quad \left(\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137} \right)$$

Scattering from an extended charge distribution: multiply σ_M by a "form factor":

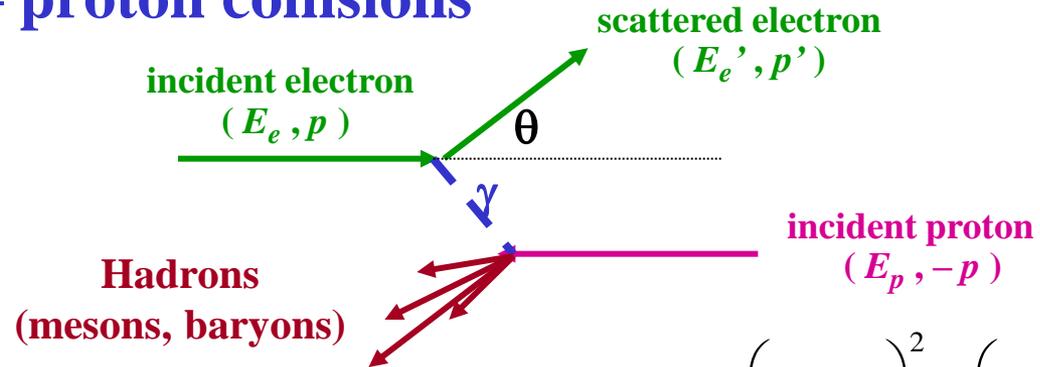
$$\frac{d\sigma}{d\Omega} = F(|Q^2|) \sigma_M$$

**$|Q| = \hbar / D$: mass of the exchanged virtual photon
D: linear size of target region contributing to scattering
Increasing $|Q| \Rightarrow$ decreasing target electric charge**

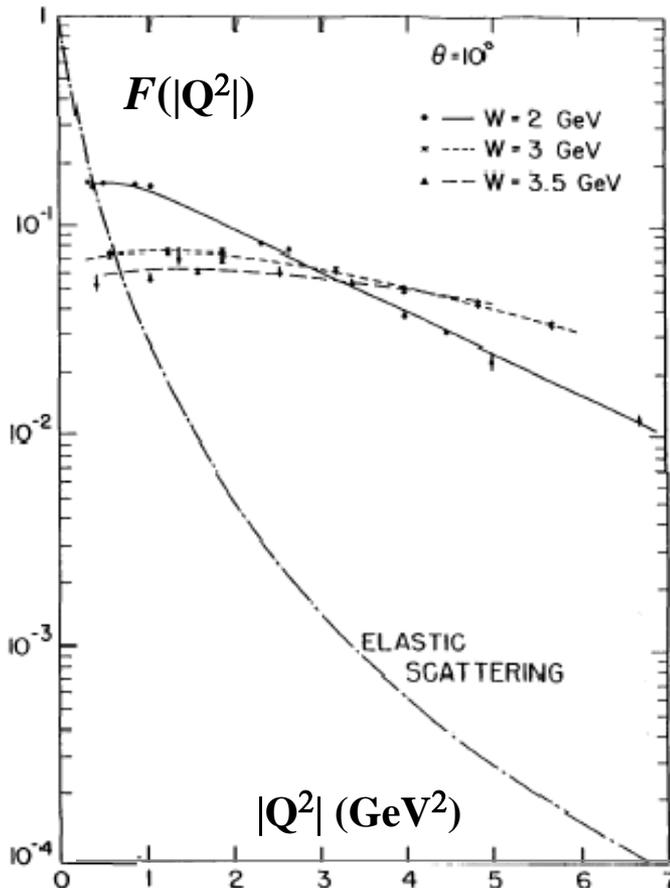


**$F(|Q^2|) = 1$ for a point-like particle
 \Rightarrow the proton is not a point-like particle**

Inelastic electron – proton collisions



Total hadronic energy : $W^2 = \left(\sum_i E_i \right)^2 - \left(\sum_i \vec{p}_i \right)^2 c^2$



For deeply inelastic collisions, the cross-section depends only weakly on $|Q^2|$, suggesting a collision with a POINT-LIKE object

Interpretation of deep inelastic e - p collisions

Deep inelastic electron – proton collisions are elastic collisions with point-like, electrically charged, spin $1/2$ constituents of the proton carrying a fraction x of the incident proton momentum

Each constituent type is described by its electric charge e_i (units of $|e|$) and by its x distribution (dN_i/dx) (“structure function”)

If these constituents are the u and d quarks, then deep inelastic e – p collisions provide information on a particular combination of structure functions:

$$\left(\frac{dN}{dx} \right)_{e-p} = e_u^2 \frac{dN_u}{dx} + e_d^2 \frac{dN_d}{dx}$$

Comparison with $\nu_\mu - p$ and $\bar{\nu}_\mu - p$ deep inelastic collisions at high energies under the assumption that these collisions are also elastic scatterings on quarks

$$\nu_\mu + p \rightarrow \mu^- + \text{hadrons} : \nu_\mu + d \rightarrow \mu^- + u \quad (\text{depends on } dN_d/dx)$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \text{hadrons} : \bar{\nu}_\mu + u \rightarrow \mu^+ + d \quad (\text{depends on } dN_u/dx)$$

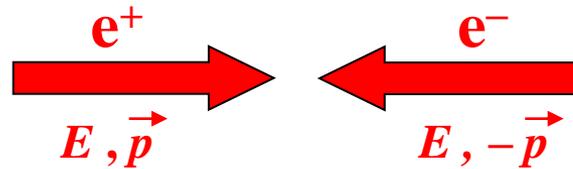
(Neutrino interactions do not depend on electric charge)

All experimental results on deep inelastic e – p , $\nu_\mu - p$, $\bar{\nu}_\mu - p$ collisions are consistent with $e_u^2 = 4/9$ and $e_d^2 = 1/9$

 the proton constituents are the quarks

PHYSICS WITH e^+e^- COLLIDERS

Two beams circulating in opposite directions in the same magnetic ring and colliding head-on



A two-step process: $e^+ + e^- \rightarrow$ virtual photon $\rightarrow f + \bar{f}$

f : any electrically charged elementary spin $1/2$ particle (μ , quark)
 (excluding e^+e^- elastic scattering)

Virtual photon energy – momentum: $E_\gamma = 2E, p_\gamma = 0 \Rightarrow Q^2 = E_\gamma^2 - p_\gamma^2 c^2 = 4E^2$

Cross - section for $e^+e^- \rightarrow f \bar{f}$:
$$\sigma = \frac{2\pi\alpha^2 \hbar^2 c^2}{3Q^2} e_f^2 \beta(3 - \beta)$$

$\alpha = e^2/(\hbar c) \approx 1/137$

e_f : electric charge of particle f (units $|e|$)

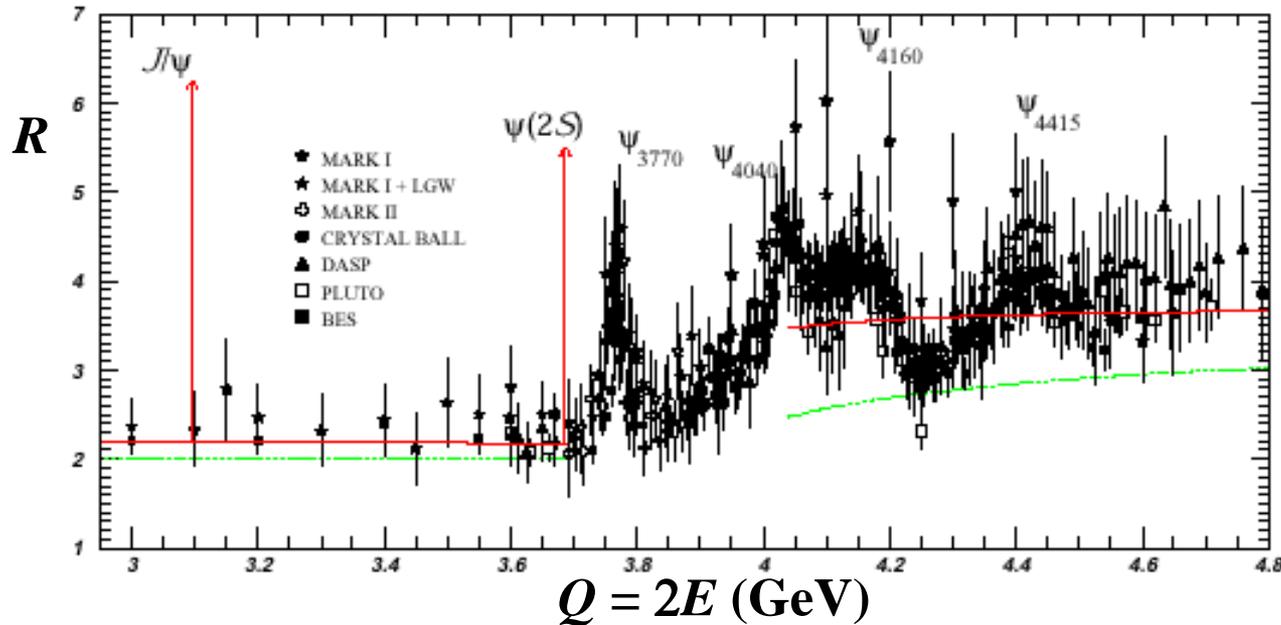
$\beta = v/c$ of outgoing particle f

(formula precisely verified for $e^+e^- \rightarrow \mu^+\mu^-$)

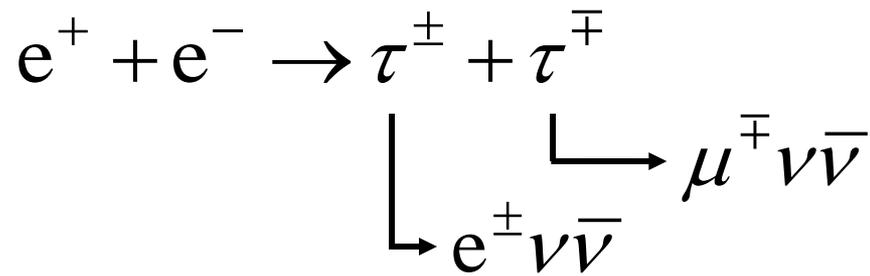
Assumption: $e^+e^- \rightarrow$ quark (q) + antiquark (\bar{q}) \rightarrow hadrons
 \Rightarrow at energies $E \gg m_q c^2$ (for $q = u, d, s$) $\beta \approx 1$:

$$R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = e_u^2 + e_d^2 + e_s^2 = \frac{4}{9} + \frac{1}{9} + \frac{1}{9} = \frac{2}{3}$$

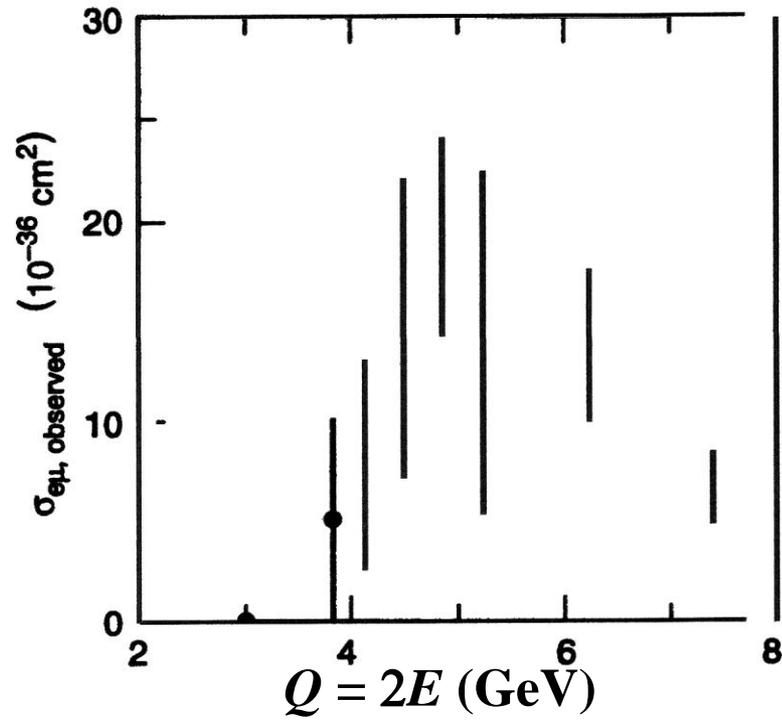
Experimental results from the Stanford e^+e^- collider SPEAR (1974–75):



- For $Q < 3.6$ GeV $R \approx 2$. If each quark exists in three different states, $R \approx 2$ is consistent with $3 \times (2/3)$. This would solve the Ω^- problem.
- Between 3 and 4.5 GeV, the peaks and structures are due to the production of quark-antiquark bound states and resonances of a fourth quark (“charm”, c) of electric charge $+2/3$
- Above 4.6 GeV $R \approx 4.3$. Expect $R \approx 2$ (from u, d, s) + $3 \times (4/9) = 3.3$ from the addition of the c quark alone. So the data suggest pair production of an additional elementary spin $1/2$ particle with electric charge = 1 (later identified as the τ – lepton (no strong interaction) with mass ≈ 1777 MeV/ c^2).



**Final state : an electron – muon pair
+ missing energy**



Evidence for production of pairs of heavy leptons τ^{\pm}

THE MODERN THEORY OF STRONG INTERACTIONS:

the interactions between quarks based on “Colour Symmetry”
Quantum ChromoDynamics (QCD) formulated in the early 1970’s

- **Each quark exists in three states of a new quantum number named “colour”**
- **Particles with colour interact strongly through the exchange of spin 1 particles named “gluons”, in analogy with electrically charged particles interacting electromagnetically through the exchange of spin 1 photons**

A MAJOR DIFFERENCE WITH THE ELECTROMAGNETIC INTERACTION

Electric charge: positive or negative

Photons have no electric charge and there is no direct photon-photon interaction

Colour: three varieties

Mathematical consequence of colour symmetry: the existence of eight gluons with eight variety of colours, with direct gluon – gluon interaction

- **The observed hadrons (baryons, mesons) are colourless combinations of coloured quarks and gluons**
- **The strong interactions between baryons, mesons is an “apparent” interaction between colourless objects, in analogy with the apparent electromagnetic interaction between electrically neutral atoms**

Free quarks, gluons have never been observed experimentally; only indirect evidence from the study of hadrons – WHY?

CONFINEMENT: coloured particles are confined within colourless hadrons because of the behaviour of the colour forces at large distances

The attractive force between coloured particles increases with distance \Rightarrow increase of potential energy \Rightarrow production of quark – antiquark pairs which neutralize colour \Rightarrow formation of colourless hadrons (hadronization)

At high energies (e.g., in $e^+e^- \rightarrow q + \bar{q}$) expect the hadrons to be produced along the initial direction of the $q - \bar{q}$ pair \Rightarrow production of hadronic “jets”

CONFINEMENT, HADRONIZATION: properties deduced from observation. So far, the properties of colour forces at large distance have no precise mathematical formulation in QCD.

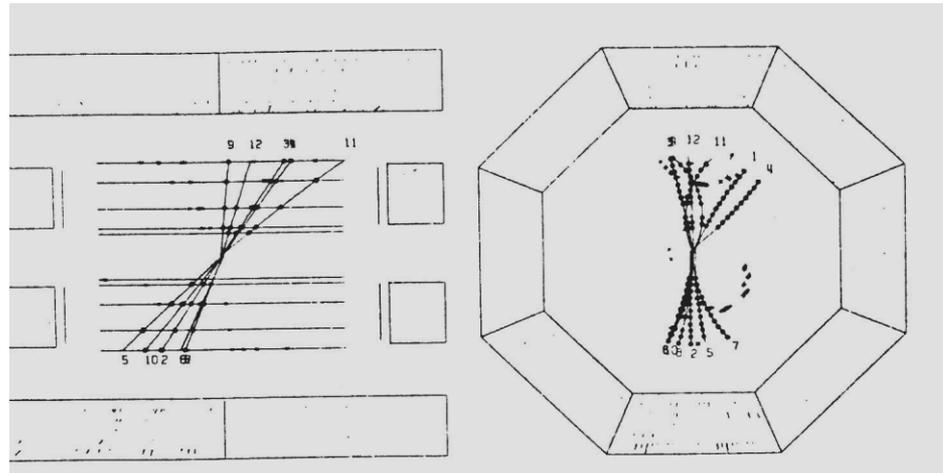
$e^+ + e^- \rightarrow \text{hadrons}$

A typical event at

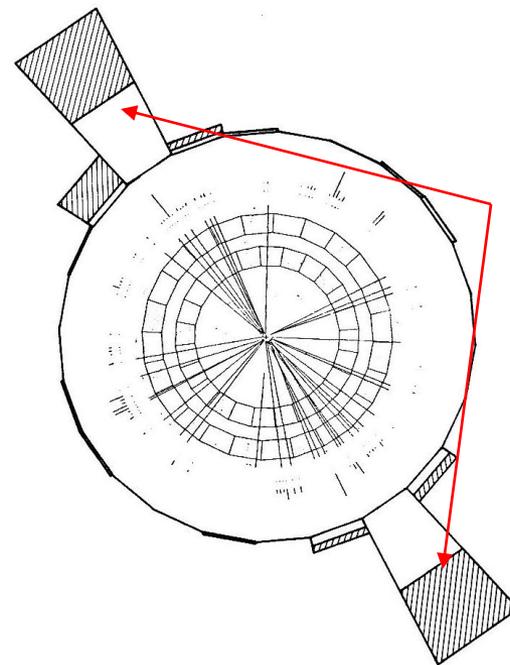
$Q = 2E = 35 \text{ GeV}$:

reconstructed

charged particle tracks



A typical proton-antiproton collision
at the CERN $\bar{p}p$ collider (630 GeV)
producing high-energy hadrons at
large angles to the beam axis
(UA2 experiment, 1985)



Energy depositions
in calorimeters

1962-66: Formulation of a Unified Electroweak Theory (Glashow, Salam, Weinberg)

4 intermediate spin 1 interaction carriers (“bosons”):

- **the photon (γ)**
responsible for all electromagnetic processes
- **three weak, heavy bosons W^+ W^- Z**
 W^\pm responsible for processes with electric charge transfer = ± 1
(Charged Current processes)

Examples:

$n \rightarrow p e^- \bar{\nu}$: $n \rightarrow p + W^-$ followed by $W^- \rightarrow e^- \bar{\nu}$

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$: $\mu^+ \rightarrow \bar{\nu}_\mu + W^+$ followed by $W^+ \rightarrow e^+ \nu_e$

**Z responsible for weak processes with no electric charge transfer
(Neutral Current processes)**

PROCESSES NEVER OBSERVED BEFORE

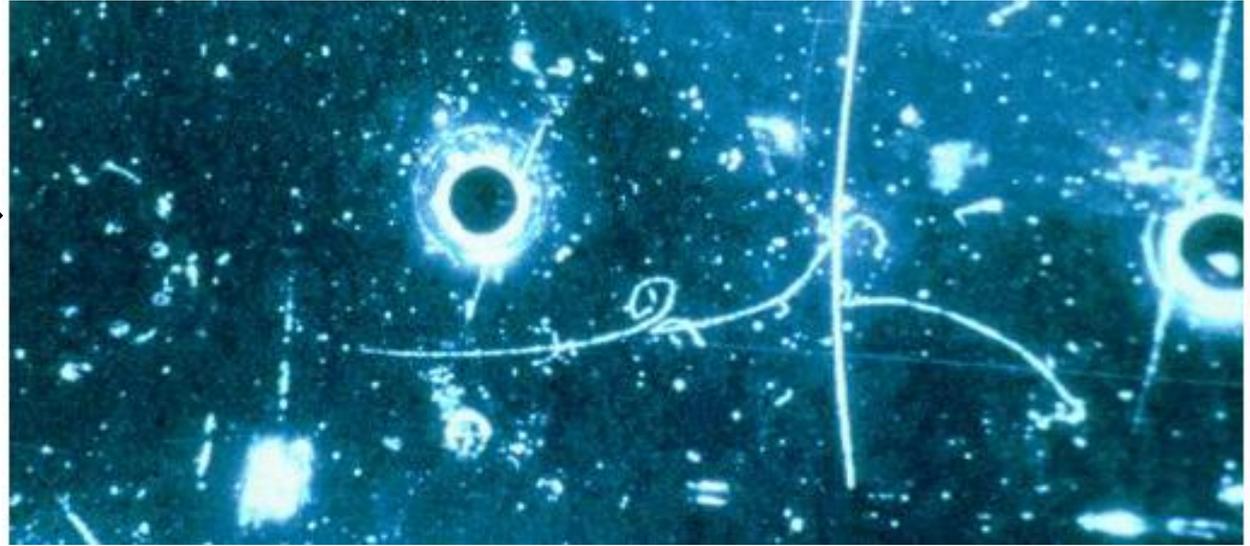
**Require neutrino beams to search for these processes, to remove
the much larger electromagnetic effects expected with charged
particle beams**

First observation of Neutral Current processes in the heavy liquid bubble chamber Gargamelle at the CERN PS (1973)

Example of

$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$
(elastic scattering)

**Recoil electron
energy = 400 MeV**

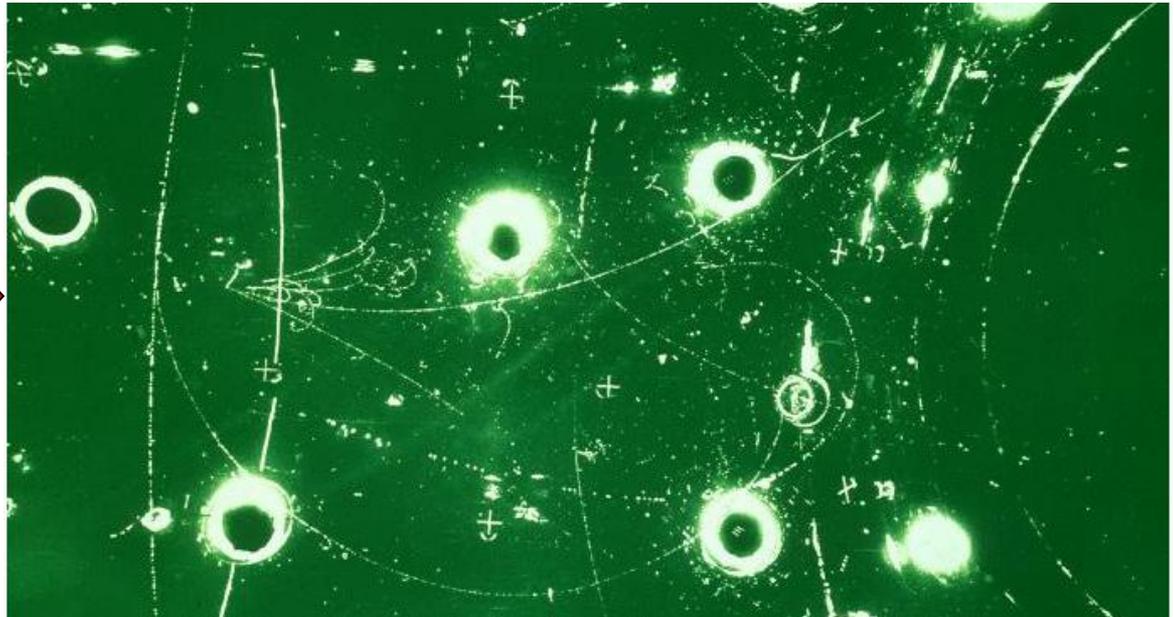


($\bar{\nu}_\mu$ beam from π^- decay
in flight)

Example of

$\nu_\mu + p (n) \rightarrow \nu_\mu + \text{hadrons}$
(inelastic interaction)

(ν_μ beam from π^+ decay
in flight)

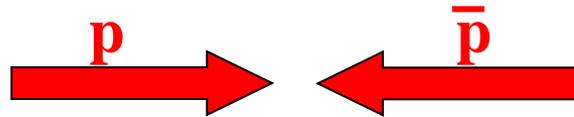


Measured rates of Neutral Current events \Rightarrow estimate of the W and Z masses (not very accurately, because of the small number of events):

$$M_W \approx 70 - 90 \text{ GeV}/c^2 \quad ; \quad M_Z \approx 80 - 100 \text{ GeV}/c^2$$

too high to be produced at any accelerator in operation in the 1970's

1975: Proposal to transform the new 450 GeV CERN proton synchrotron (SPS) into a proton – antiproton collider (C. Rubbia)



Beam energy = 315 GeV \Rightarrow total energy in the centre-of-mass = 630 GeV

Beam energy necessary to achieve the same collision energy on a proton at rest :

$$(E + m_p c^2)^2 - p^2 c^2 = (630 \text{ GeV})^2 \quad \Rightarrow \quad E = 210 \text{ TeV}$$

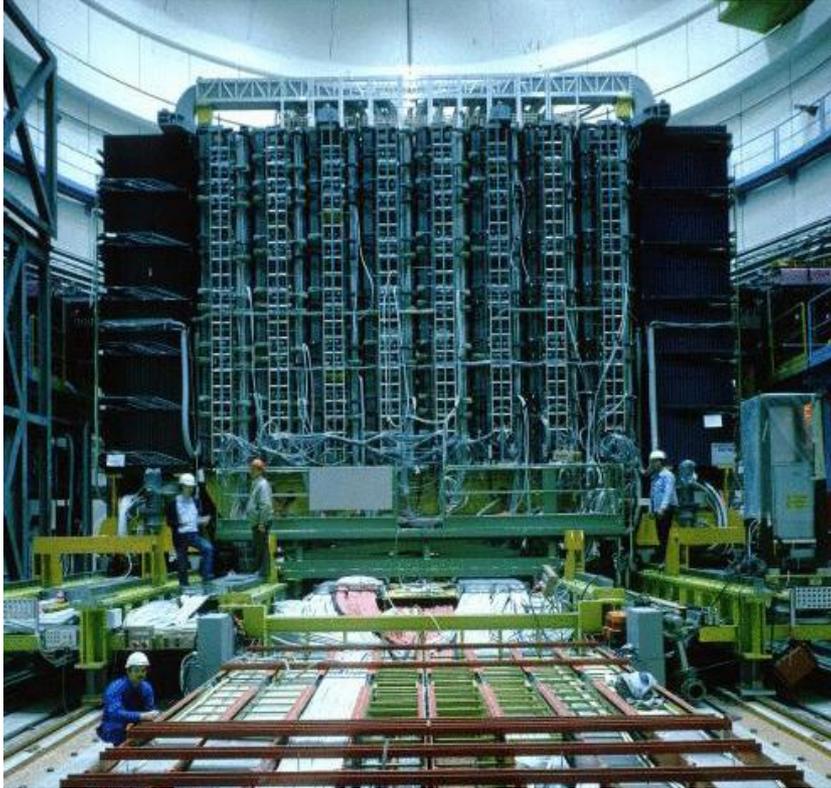
Production of W and Z by quark – antiquark annihilation:

$$u + \bar{d} \rightarrow W^+ \quad \bar{u} + d \rightarrow W^-$$

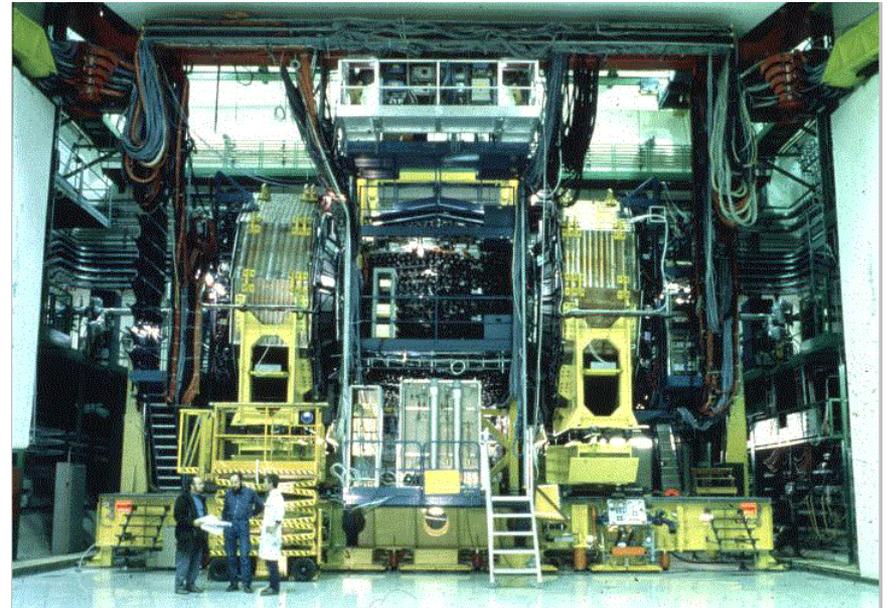
$$u + \bar{u} \rightarrow Z \quad d + \bar{d} \rightarrow Z$$

UA1 and UA2 experiments (1981 – 1990)

Search for $W^\pm \rightarrow e^\pm + \nu$ (UA1, UA2) ; $W^\pm \rightarrow \mu^\pm + \nu$ (UA1)
 $Z \rightarrow e^+e^-$ (UA1, UA2) ; $Z \rightarrow \mu^+ \mu^-$ (UA1)

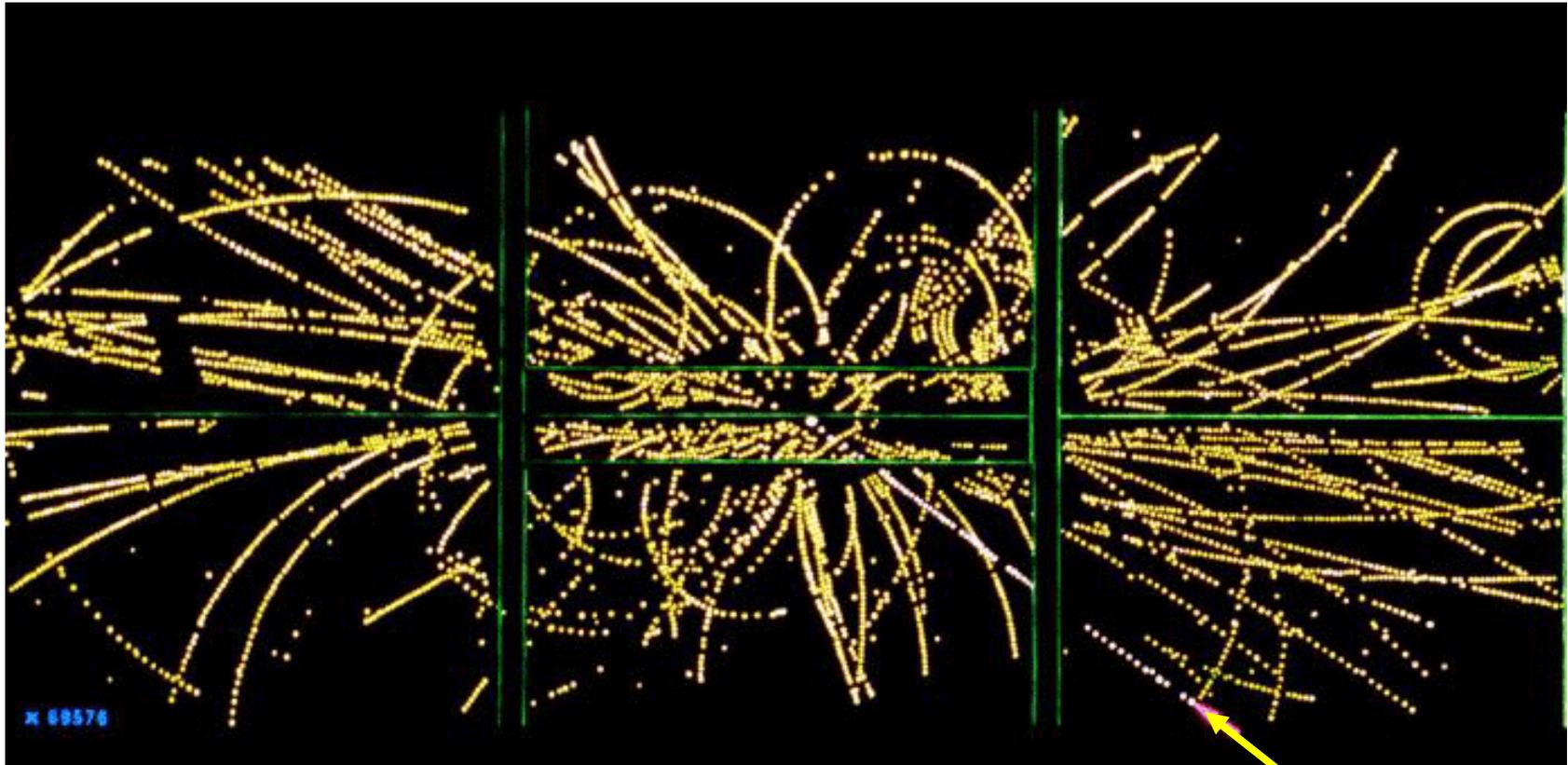


UA1: magnetic volume with trackers,
surrounded by “hermetic” calorimeter
and muon detectors



UA2: non-magnetic,
calorimetric detector
with inner tracker

One of the first $W \rightarrow e + \nu$ events in UA1



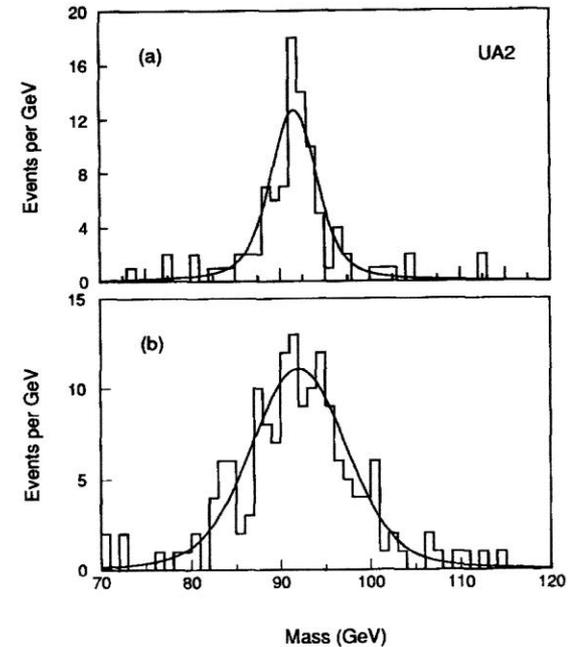
**48 GeV electron
identified by
surrounding calorimeters**

UA2 final results

Events containing two high-energy electrons:
Distributions of the “invariant mass” M_{ee}

$$(M_{ee}c^2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 c^2$$

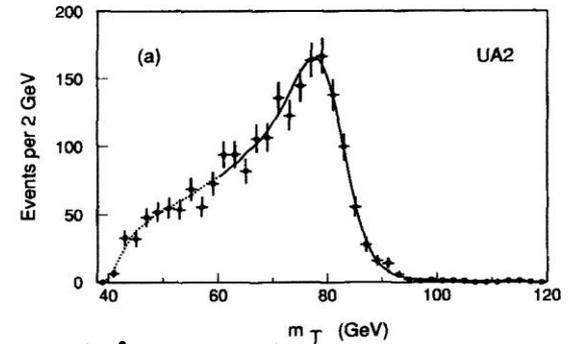
(for $Z \rightarrow e^+e^-$ $M_{ee} = M_Z$)



Events containing a single electron with large transverse momentum (momentum component perpendicular to the beam axis) and large missing transverse momentum (apparent violation of momentum conservation due to the escaping neutrino from $W \rightarrow e\nu$ decay)

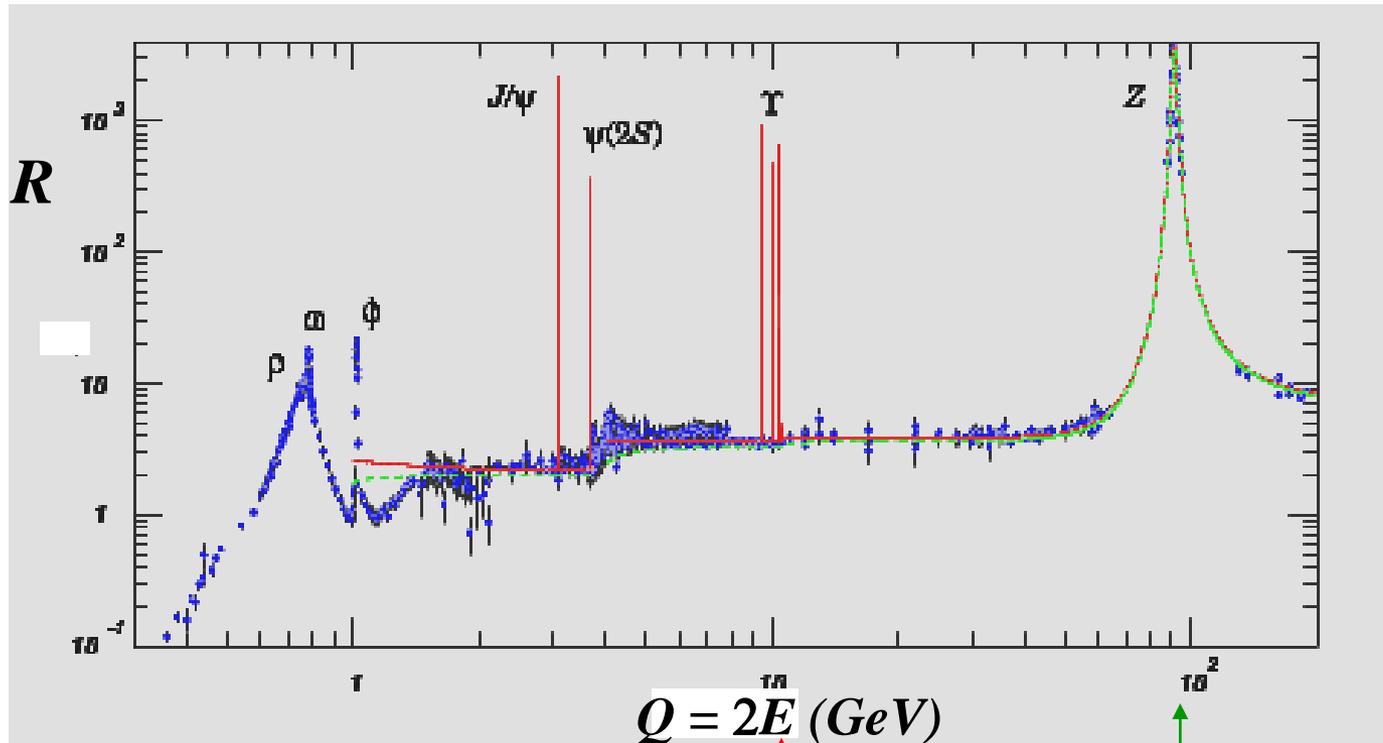
m_T (“transverse mass”): invariant mass of the electron – neutrino pair calculated from the transverse components only

M_W is determined from a fit to the m_T distribution: $M_W = 80.35 \pm 0.37 \text{ GeV}/c^2$



e^+e^- colliders at higher energies

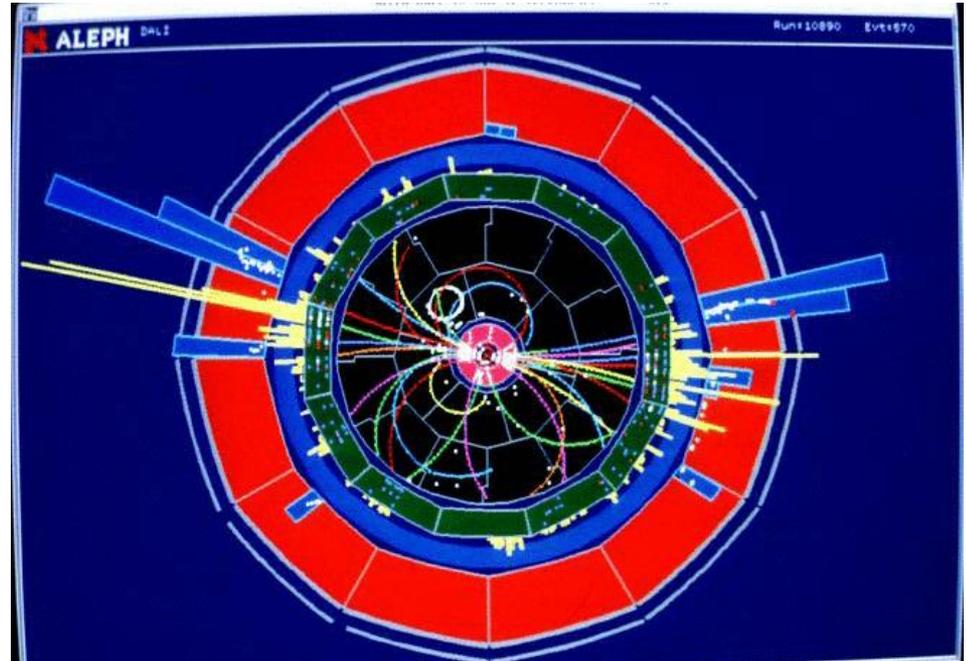
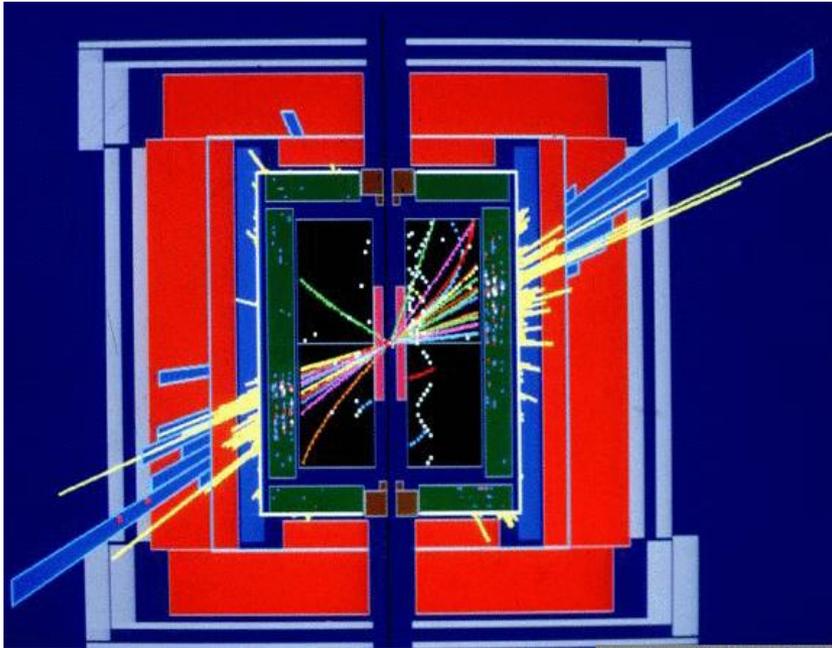
$$R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \quad \text{between } 0.3 \text{ and } 200 \text{ GeV}$$



$e^+e^- \rightarrow b \bar{b}$
(the 5th quark: $e = -1/3$)

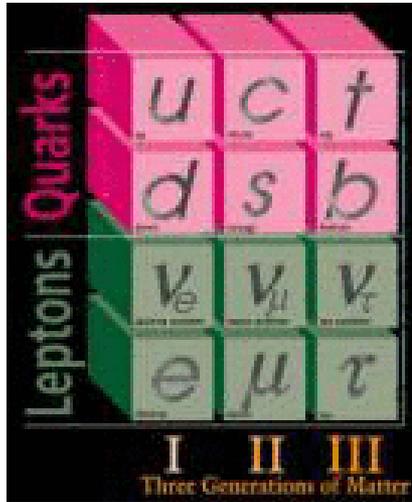
$e^+e^- \rightarrow Z \rightarrow q \bar{q}$

The two orthogonal views of an event $Z \rightarrow q \bar{q} \rightarrow$ hadrons at LEP (ALEPH detector)



CONCLUSIONS

The elementary particles today:



3 x 6 = 18 quarks

+ 6 leptons

= 24 fermions (constituents of matter)

+ 24 antiparticles

48 elementary particles

consistent with point-like dimensions within the resolving power of present instrumentation ($\sim 10^{-16}$ cm)



12 force carriers (γ , W^\pm , Z, 8 gluons)

**+ the Higgs spin 0 particle (NOT YET DISCOVERED)
responsible for generating the masses of all particles**