142.091 Particle Physics

Concepts and Experimental Tests

Aim of Lectures
Overview
Course
Exam

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Fall Term 2010

Elementary Particle Physics: Aim of lectures

- Qualitative discussion of our present understanding
- Emphasis of fundamental concepts
  - interplay between experiment and theory
  - emergence of the ‘Standard Model’ of Particle Physics
- Provide understanding of the pillars of Particle Physics
- Connection with Cosmology and Astroparticle physics
- Physics Programme at the Large Hadron Collider (LHC)
  - completing out present physics understanding
  - opening new frontiers in particle physics and cosmology
  - seeing the shortcomings of the Standard Model

Elementary Particle Physics: Program of lectures

Block 1: Major milestones of the past 100 years

From the discovery of the electron to the ‘Standard Model’ of particle physics and beyond

Block 2: Creating and detecting particles

Accelerating particles: synchrotrons and colliders
Detecting particles: measuring momentum, energy, mass, lifetime of particles

Two case studies:
Discovery of the antiproton
Discovery of the W- and Z-bosons

Block 3: Fundamentals

Four forces; quarks and leptons
Conservation laws; unification schemes

Elementary Particle Physics: Program of lectures

Block 4: Components of the Standard Model (a)

Quantumelectrodynamics
Quantumchromodynamics

Block 5: Symmetries and symmetry breaking

Parity, charge-parity and violations
Case study of interplay between theory and experiment
Nuclei, *K*- and *B*-meson systems
How did the Universe become matter-dominated ?

Block 6: Components of the Standard Model (b)

The electroweak force

Elementary Particle Physics: Program of lectures

Block 7: The neutrinos: 80 years of scientific drama – and no end in sight

Pauli postulation

The discovery

40 years of solar neutrino puzzle and its spectacular resolve

Block 8: The research frontier: LHC, Belle II, FAIR, Precision Experiments

The open issues

The cosmos – connection

Summary

Block 1: Major Milestones of the past 100 years

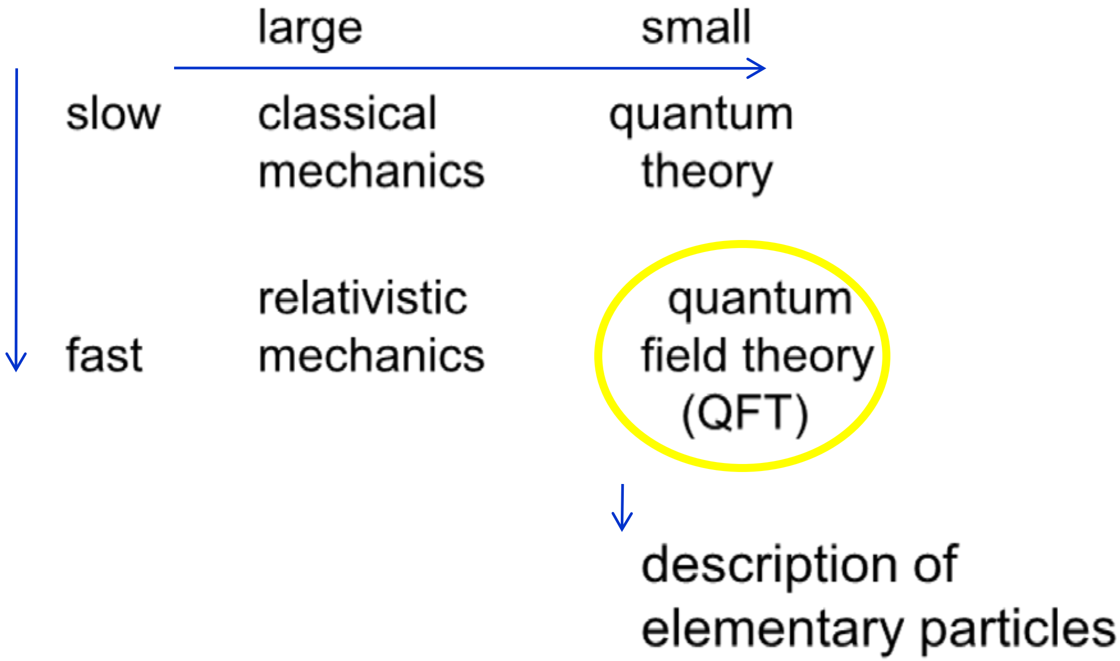
- Discovering the constituents of the atom
- The first surprise: too many elementary particles
- The ‘Periodic System’ of elementary particles
- The beauty of Symmetries: non-perfect is better!
- Quarks: a mathematical intuition turns into a surprising physical reality
- Synthesis: elements of the ‘Standard Model’ of Particle Physics

Particle Physics: General remarks

- Particle Physics
  - what is matter made of ?
  - how is matter formed ?
- Matter
  - tiny bits of matter with lots of empty space (e.g. an atom)
  - matter comes in limitless variety, but
  - only few different bits (‘constituents’) of matter ⇒ ‘an electron is an electron is an electron’
- Elementary Particles
  - too small to be observed directly
  - indirect evidence
    - ○ scattering between particles: force between; size of particles
    - ○ bound states: interaction between constituents
    - ○ creating new particles

Particle Physics: General remarks

- Theoretical Description



	large	small
slow	classical mechanics	quantum theory
fast	relativistic mechanics	quantum field theory (QFT)

↓

description of elementary particles

Particle Physics: General comments

- Note: certain features follow directly from the theory

  Example: Relativity

  - energy *E*, momentum *p* are conserved , but
  - rest mass is NOT conserved
    - particle decay $\Delta \rightarrow p + \pi$ is perfectly possible, although

      $$m_\Delta > m_p + m_\pi$$

    - particle with rest mass $m = 0$ is allowed (nonsense in classical mechanics)

  Example: Quantum Mechanics

    - system described by state |*s*> and wave function ψ - result is probabilistic description (lifetime, transition of excited atomic state, decay into different channels)

Particle Physics: General comments

Example: Quantum Field Theory

- Pauli Exclusion Principle
- existence of Antiparticles
- invariance under combined operation of
  - o P (parity)
  - o C (Charge Conjugation)
  - o T (Time reversal)

Example: Standard Model (SM) of Particle Physics

- all three interactions

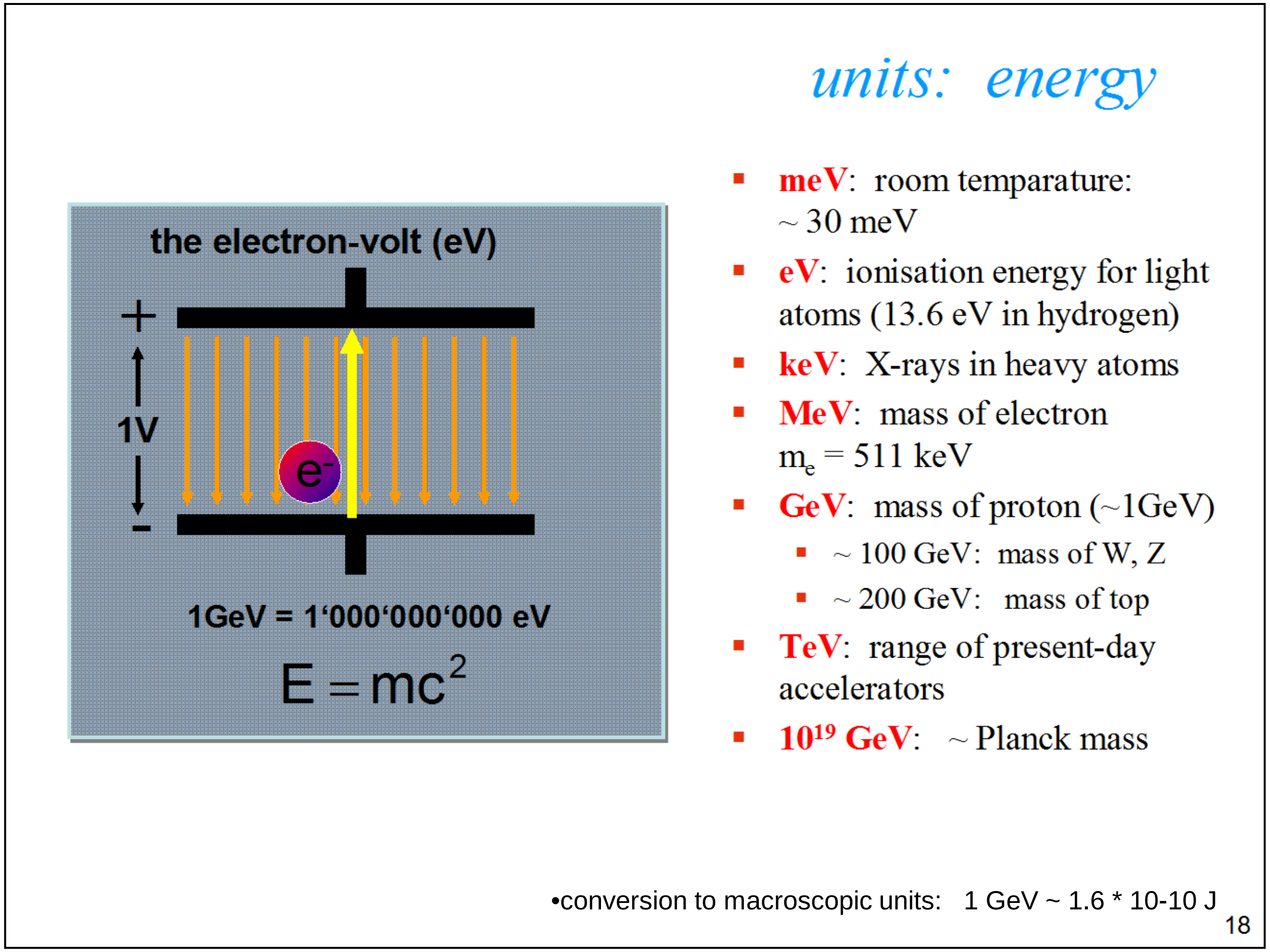
o weak

o electromagnetic

o strong

can be derived from the requirement of ‘local gauge invariance’

Units in Particle Physics



units: energy

the electron-volt (eV)

1GeV = 1‘000‘000‘000 eV

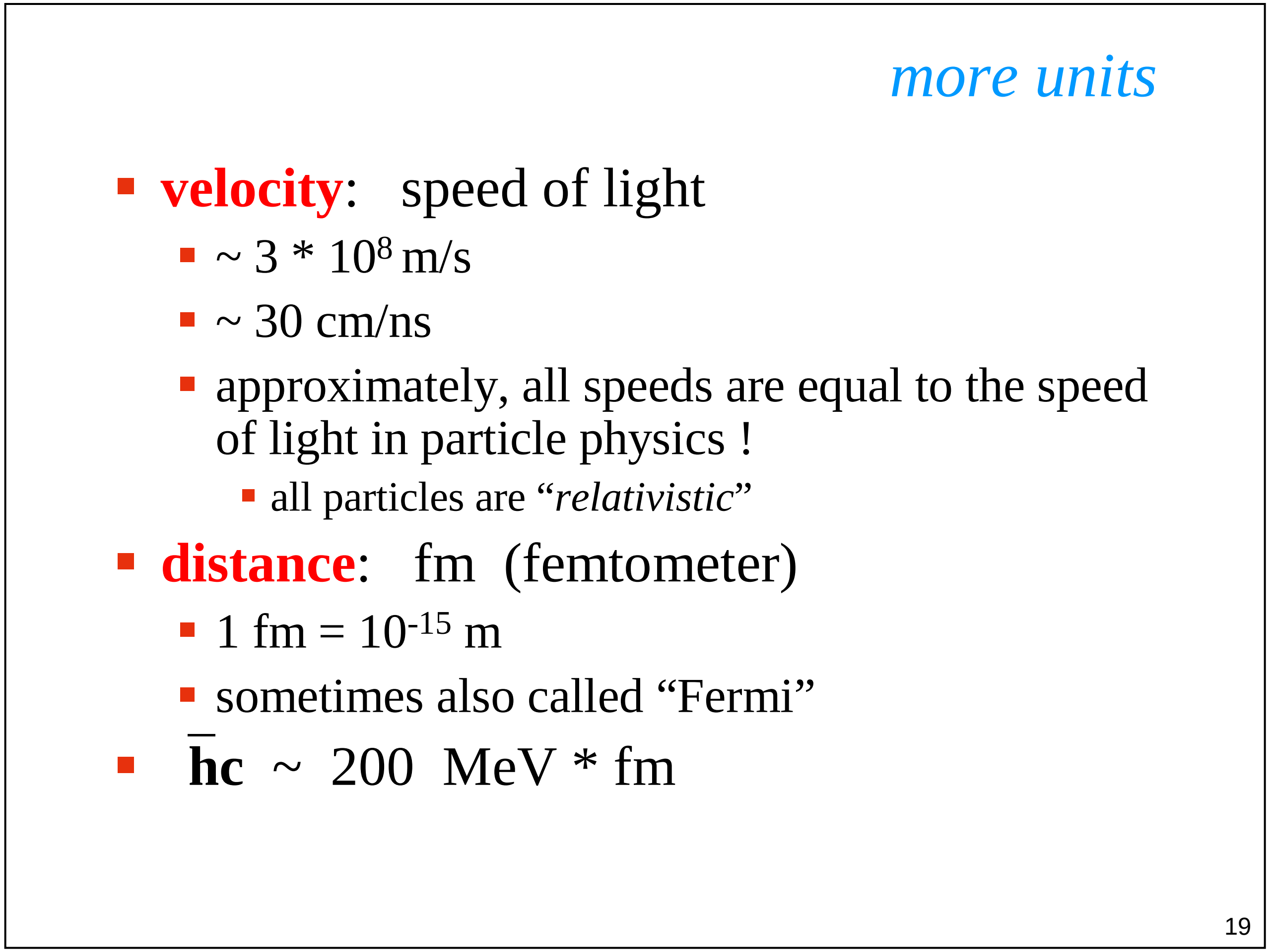
$$E = mc^2$$

- **meV**: room temparature: ~ 30 meV
- **eV**: ionisation energy for light atoms (13.6 eV in hydrogen)
- **keV**: X-rays in heavy atoms
- **MeV**: mass of electron m_e = 511 keV
- **GeV**: mass of proton (~1GeV)
  - ~ 100 GeV: mass of W, Z
  - ~ 200 GeV: mass of top
- **TeV**: range of present-day accelerators
- **10^{19} GeV**: ~ Planck mass

•conversion to macroscopic units: 1 GeV ~ 1.6 * 10-10 J

From M. Jeitler

More units



more units

- **velocity**: speed of light
  - ~ 3 * 10^8 m/s
  - ~ 30 cm/ns
  - approximately, all speeds are equal to the speed of light in particle physics !
    - all particles are “*relativistic*”
- **distance**: fm (femtometer)
  - 1 fm = 10^{-15} m
  - sometimes also called “Fermi”
- $\hbar c \sim 200$ MeV * fm

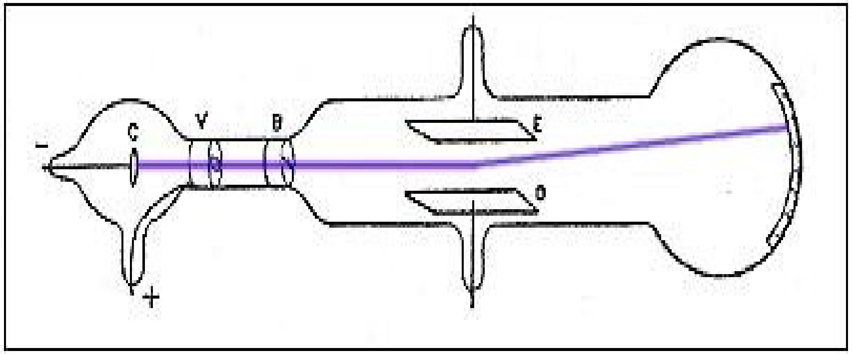
The First 100 Years: milestones of particle physics

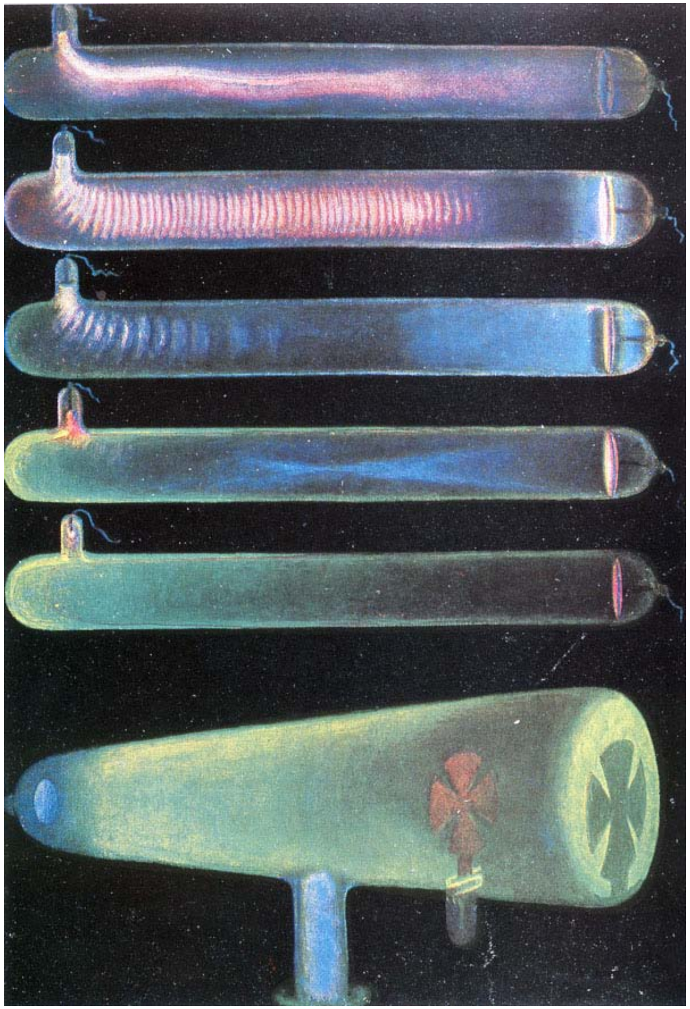
1897: Electron discovered by J.J. Thompson

- cathode rays deflected by electric field -> are really particles, not ‘rays’
  - with crossed electric and magnetic fields ->
    $q E = qvB$ -> velocity v
  - Radius of curvature in B field $R=mv/ qB$
  - Determination of m/q …~ 10^{-7} (actual:~ $6*10^{-7}$)

- discovery led to model of the atom (is neutral)
  - o electrons are ‘plums’ in charged pudding

J.J. Thompson and the Discovery of the electron





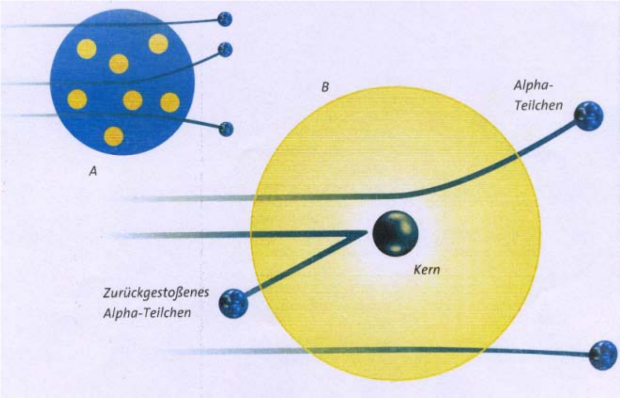
The First 100 Years: Proton; discovery of nucleus

1905: Proton (Rutherford)

- first scattering experiment in particle physics
- energetic particles used to ‘see’ (probe) structure of system
- Rutherford scattered α-particles in gold
  - deflection of α-particles depends on the charge distribution of scattering center
  - observed occasional large deflection ⇒ inconsistent with ‘plum pudding’ model (one event in 8000)
  - positive charge in concentrated ‘nucleus’
  - Rutherford calls lightest nucleus (hydrogen) ‘proton’

The first scattering experiment in particle physics

- Applying the inverse-square law between the charges on the electron and nucleus, one can write:
-
- $mv^2/ 2$ (kinetic energy) = $(1/4\pi\varepsilon_0)\, q_1\, q_2 / b$ (potential energy) b..'impact parameter'
- Rearranging:
- $b= (1/4\pi\varepsilon_0)\, 2\, q_1\, q_2 / mv^2$
- For an alpha particle:
- **m** (mass) = 6.7×10^{-27} kg
- $\mathbf{q_1}$ = $2\times(1.6\times10^{-19})$ C
- $\mathbf{q_2}$ (for gold) = $79\times(1.6\times10^{-19})$ C
- **v** (initial velocity) = 2×10^{7} m/s
- Substituting these values in the above expression gives the value of about 2.7×10^{-12} cm; this is an upper limit: alpha particle does not have energy to fully approach nucleus ; true value of radius of gold is 7.3×10^{-15} m.



Scattering cross section

- Cross section defined via scattering probability W= σ n

- N...number of scatters in beam
- σ ... Cross section of individual scatterers

- Naive view: each scatter has a certain ‘area’ and is completely opaque
- Concept can also be used for elastic scattering or particle transformation, i.e differential cross section for a certain reaction
- Unit: ‘barn’: $(10\ \mathrm{fm})^2 = 10^{-24}\ \mathrm{cm}^2$

The etymology of the unit “barn” is clearly whimsical and jocular—the unit is said to be "as big as a barn" compared to the typical cross sections for nuclear reactions. During wartime research on the atomic bomb, American physicists who were deflecting neutrons off uranium nuclei, (similar to Rutherford scattering) described the uranium nucleus as “big as a barn.” Physicists working on the Manhatten project adopted the name barn for a unit equal to 10^{-24} square centimeters, about the size of a uranium nucleus. Initially they hoped the American slang name would obscure any reference to the study of nuclear structure; eventually, the word became a standard unit in particle physics.

The First 100 Years: Bohr's model of the atom; neutron

1914: Niels Bohr proposes 'planetary' model of atom

- works with certain ad-hoc postulates for hydrogen
- problem noted with $^{4}He : Z=2; M=4$
- How to explain the mass M=4, while the charge is Q=2 ?

1932: James Chadwick discovers the neutron

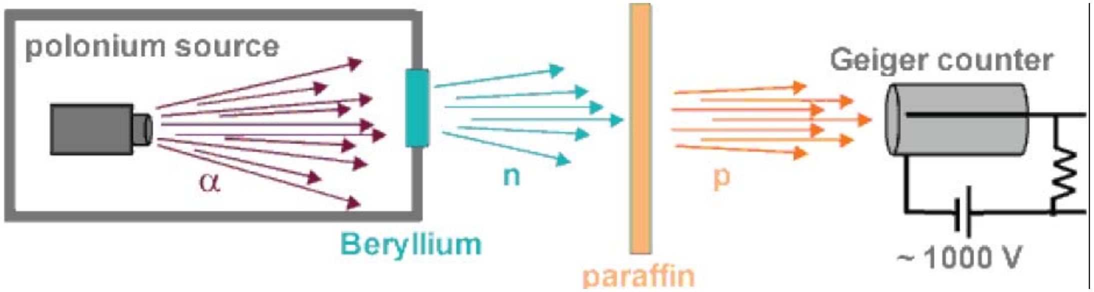
- Penetrating neutral particles of mass ≈ (proton)
- Nobel Prize in 1935

1932: First synthesis: all matter is made from

- electrons, protons, neutrons

1932: never before (and soon: never again) was our view of the world so beautifully simple ……

Neutron Discovery



- α + ^{9}Be = ^{12}C + n
- emitted radiation thought originally to be gamma radiation: penetrating; not deflected upon passing through a magnetic field; however, unlike gamma rays, they would not discharge electroscope (photoelectric effect). Curie discovered that this radiation would knock out protons in a hydrogen-rich substance
- In 1932, Chadwick proposed that this particle was Rutherford's neutron. In 1935, he was awarded the Nobel Prize for his discovery. Using kinematics, Chadwick determined the velocity of the protons; through conservation of momentum techniques: mass of the neutral radiation was almost exactly the same as that of a proton

The First 100 Years: The photon

1900: Planck describes the black body radiation spectrum postulating

- energy E emitted is quantized
- $E = h\nu$; h as a parameter to fit the measurement
- Planck's constant $h = 6{,}626 \times 10^{-27}$ erg s

1905: Einstein: explains photoelectric effect

- photon behaves like a particle
- E (photoelectron) ≤ $h\nu$ energy of photon) $-w$ (work function)
- explains that E of ph. e. depends only on ν, and NOT on intensity of light source
- this is the start of a 20 year battle between the titans of physics

The First 100 Years:
The photon – particle or wave ?

The particle-wave duality fight

- Newton – Huygens: the first round of scientific dispute
- Young: interference experiments: photon is a wave-
- Newton: light is reflected in straight lines: corpuscles
- 1916: Millikan: exhaustive study on photons and photoelectric effect, concludes:

  ‘*Einstein’s equation of the photoelectric effect appears in every case to predict the correct result; yet the semi-corpuscular theory, by which Einstein derived his equation, seems at present wholly untenable’*

  dixit a later Nobel prize winner !

[Millikan: measurement of charge of electron, Nobel Prize 1923]

The First 100 Years: Climax and finale of the duality battle

1923: Compton: light scattered from a target with mass m_e is shifted in frequency according to

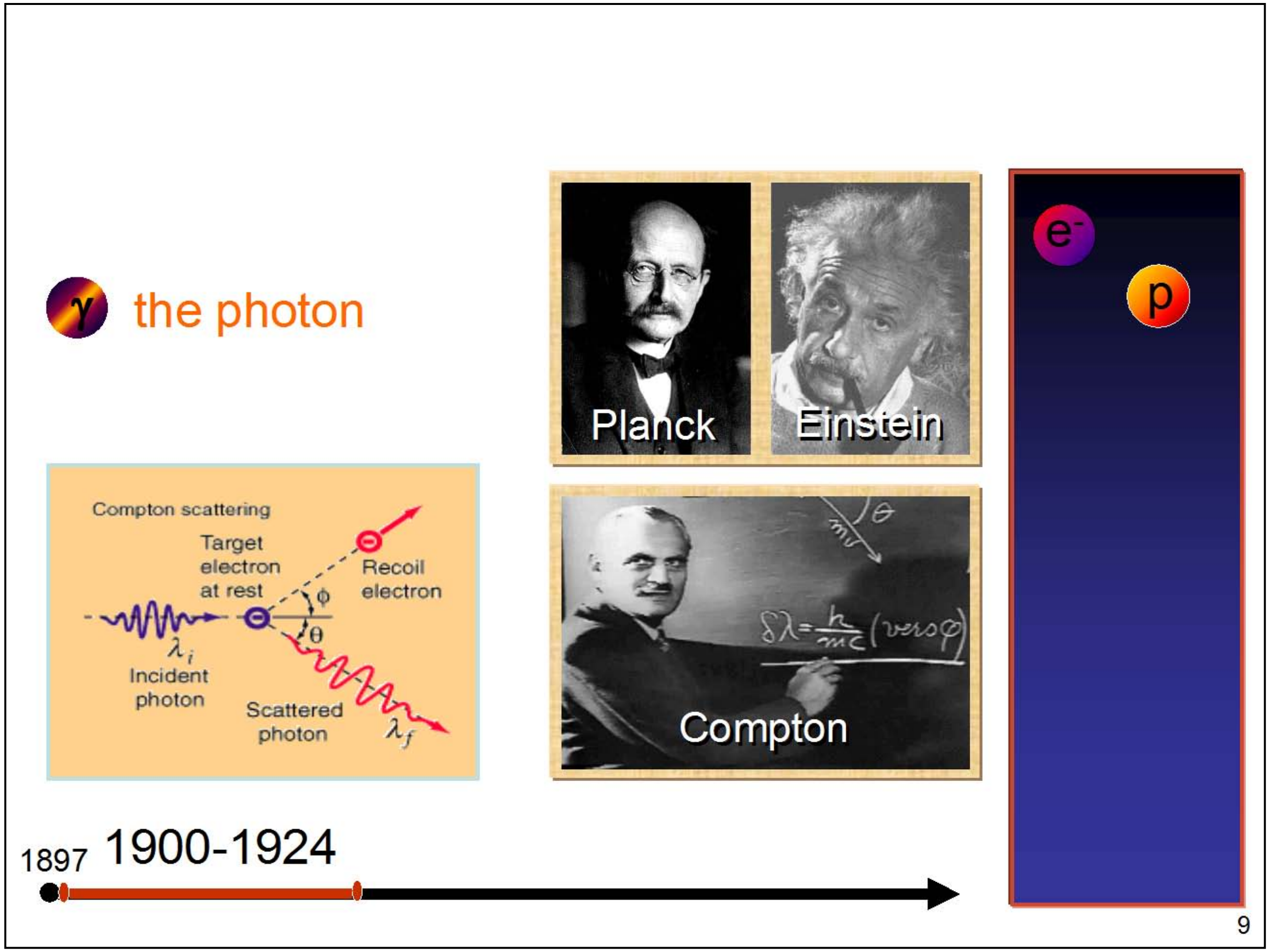
- $\lambda' = \lambda + \lambda_c\,(I - cos\,\theta)$
  $\lambda_c = h/m_e c$; θ in scattering angle
- exactly, as if particle (photon) with mass = 0 is scattered; with $\overline{p}$, E conserved
- on an atomic scale: photon behaves like a $m = 0$ particle
- Nobel Prize 1927

1926: G. Lewis proposes the name ‘Photon’

wave-particle duality is feature in quantum physics

wave-particle duality is a natural consequence in Quantum Field Theory: field is quantized, in form of photons

Modern concept of Photon



γ the photon

1897 1900-1924

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From M. Jeitler

The First 100 Years: Changing concept of ‘interaction’

Classical electromagnetism

- interaction through (electromagnetic) field
- ‘action at a distance’, mediated by field

Quantum Field Theory (e.g. Quantum electrodynamics, QED)

- field is quantized, in form of photons
- interaction mediated by ‘stream of photons’ passing back and forth between the two charges
- more general in QFT: interaction mediated by the exchange of particles (quantum of the field, γ for QED, gluons for QCD)

Imagine:

exchange of particle is like a messenger particle:

… move a bit closer, ….. move a bit apart

The First 100 Years: Mesons: 1934-1947

- Problem 1: what holds nucleus together ?
  - gravity too weak
  - em force: repulsive between protons
  - need new type of force: strong

- Problem 2: why not seen in every day life ?
  - force is ‘short-range’
    - o like interaction of a boxer: force felt within arm’s length, not beyond
    - o more correctly $F(r) = e^{-(r/a)} / r^2$
      - o $a = \infty$ for gravitational and *em* force
      - o $a \sim 10^{-13}$ cm for strong force

1934: Yukawa

Yukawa

- *p* and *n* are attracted by quantized field
- properties of 'quantum' to produce short range must be heavy
  $m \approx 300\,m$ (electron) ≈ 150 MeV/c^2
- mass of this field quantum is in between
  - o mass of electron: 'Lepton'
  - o mass of proton: 'Baryon'
  - o exchange quantum: 'Meson'
- Nobel Prize 1949

Forces betwen nucleons vs Forces between constituents of the nucleon

- Remember:
  - Electromagnetic force responsible for atomic structure
  - Atoms bound to molecules by van der Waals force, ‘sort of remnant of the electromagnetic force‘
- Constituents in Nucleon (details later) held together by ‘Strong Force‘
  - However: nucleons bound to nuclei by sort of an remnant of the strong force -> the exchange of the Yukawa Meson

1937: Anderson, Neddermeyer and Street, Stevenson

- Observation of a particle with properties compatible with ‘Yukawa’ Meson

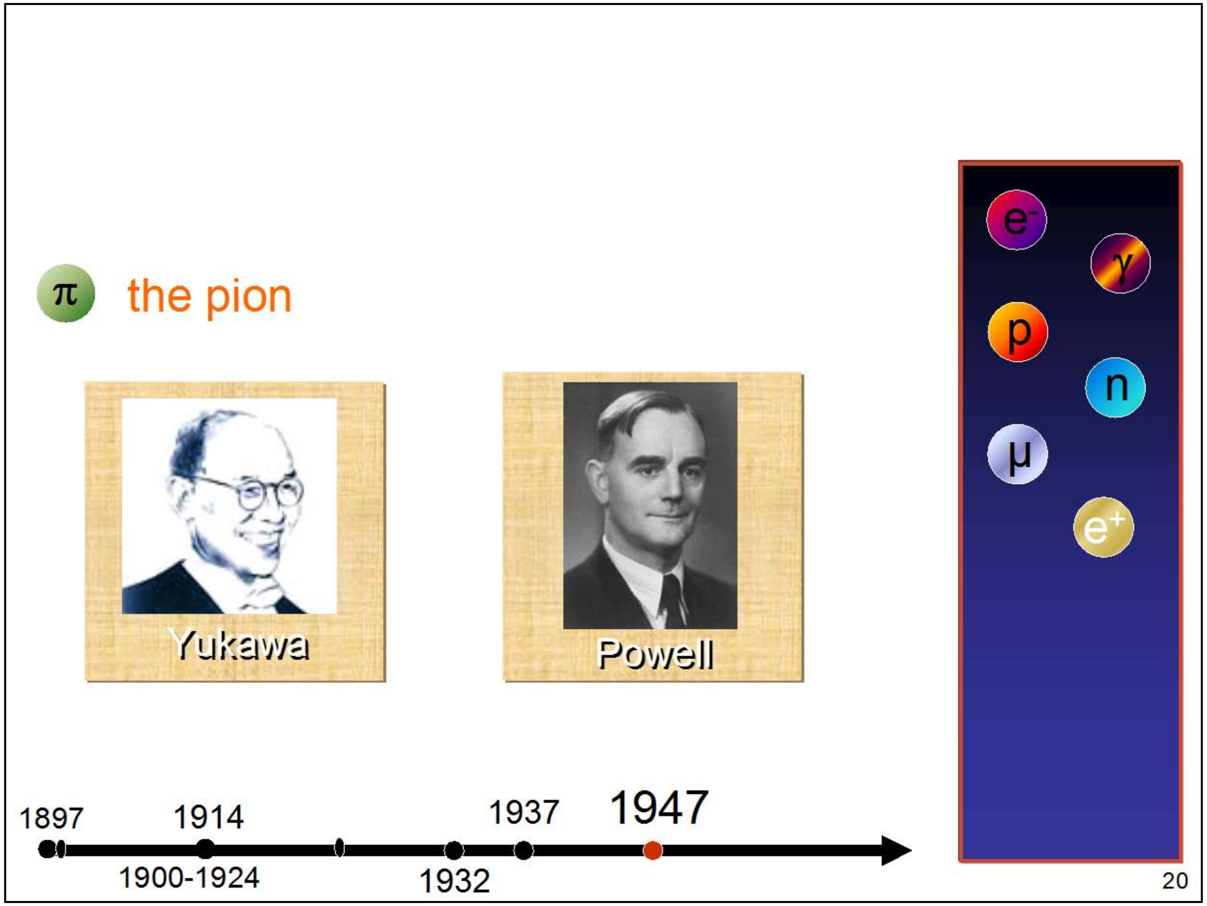
- However, confusing measurements of lifetime, interaction probabilities

- 1946: Powell and coworkers showed:
  - there are two ‘lightweight’ particles with very different properties, which they called muon (μ) and pion (π)

$m(\mu) = 105.7$ MeV $\tau(\mu) = 2.2 \times 10^{-6}$ s

$m(\pi) = 139.6$ MeV $\tau(\pi) = 2.8 \times 10^{-8}$ s

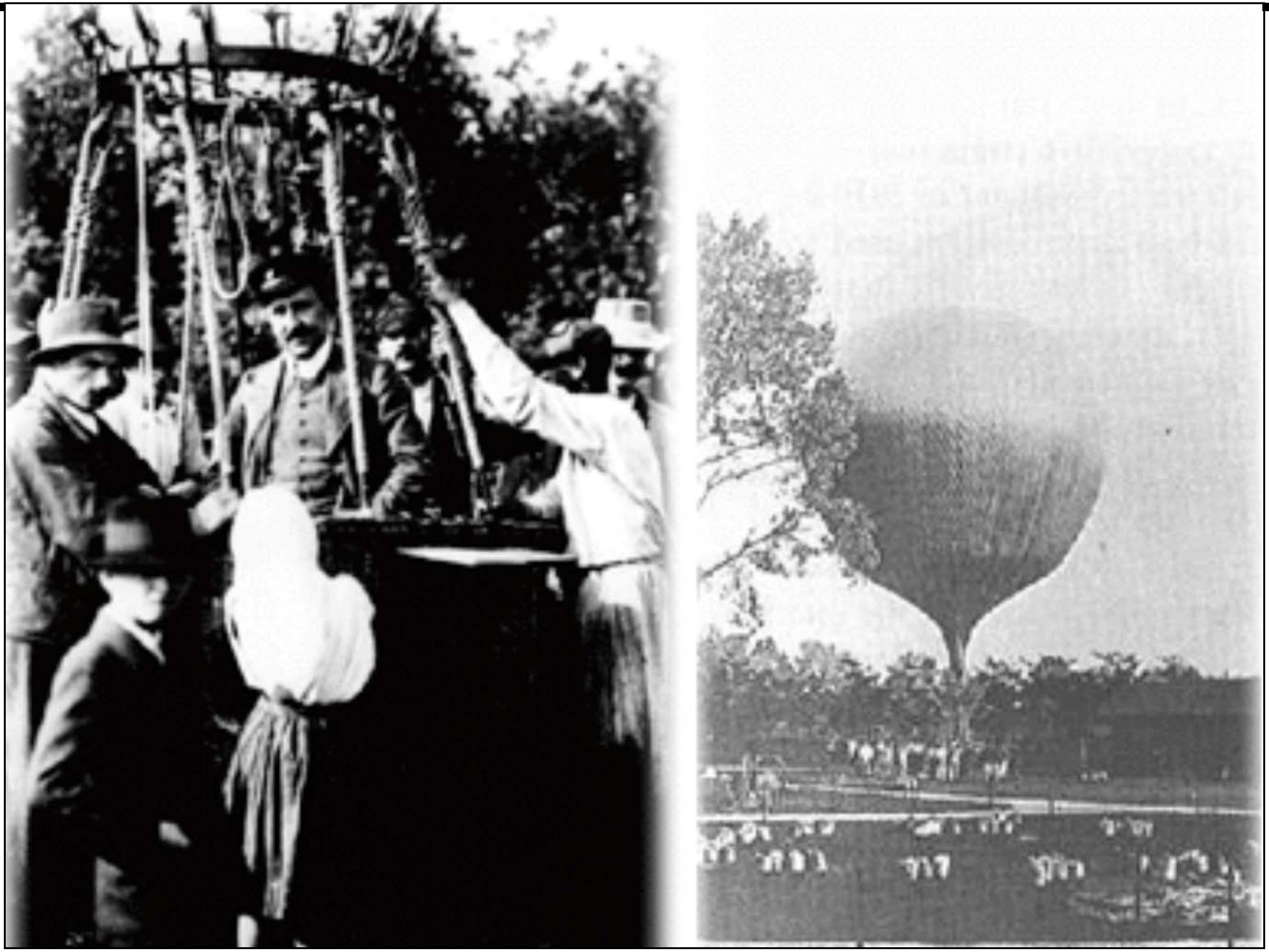
The Pion: predicted and discovered



- Yukawa calculated the pion’s mass fairly accurately
- a particle with this mass was found by *Powell* in 1947 (he got the Nobel prize in 1950; Yukawa had received the Nobel prize in 1949)
- at first, the muon found in cosmic radiation had been wrongly identified as this particle

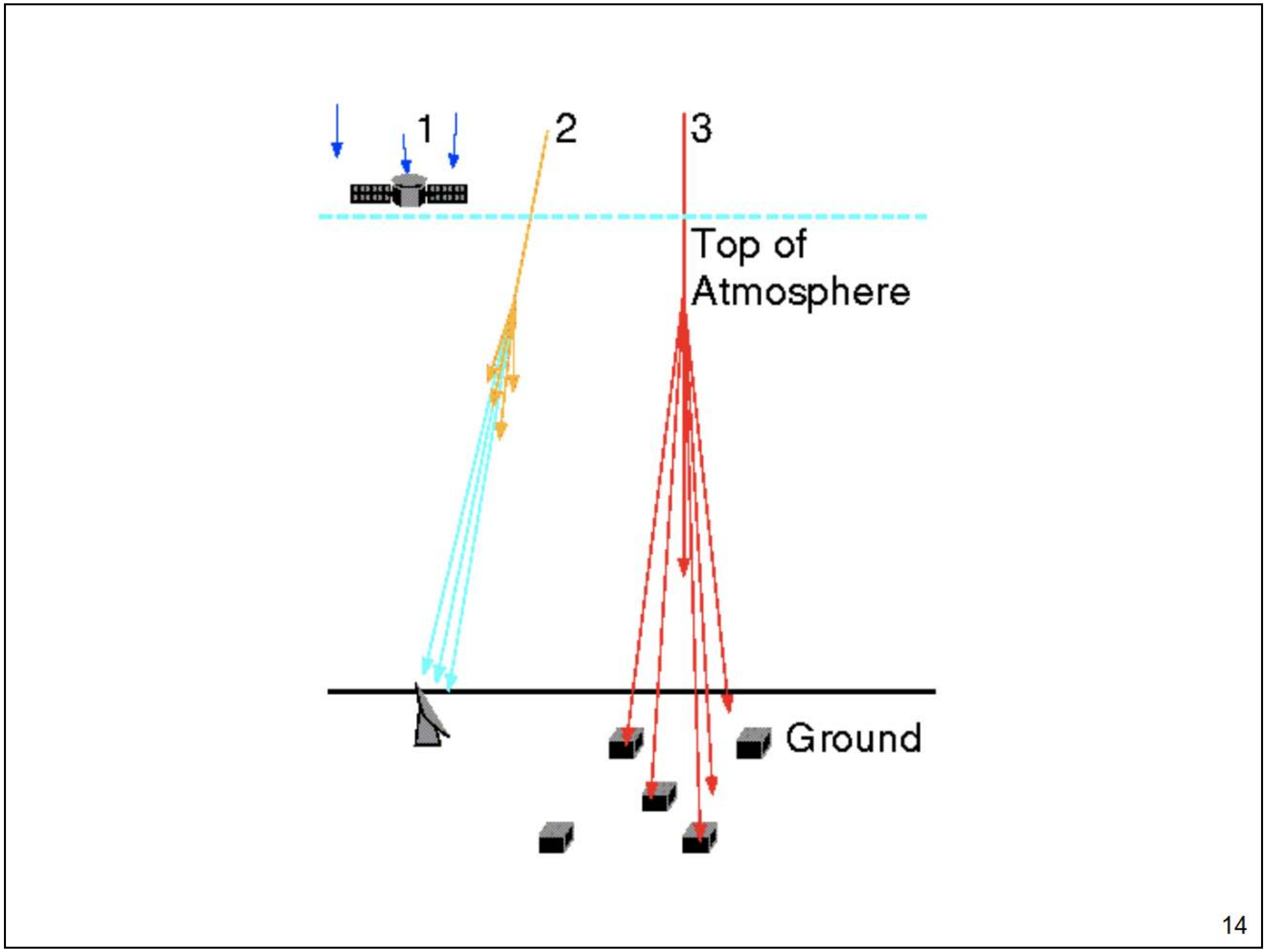
From M. Jeitler

The most powerful Particle accelerator: Cosmic Radiation



Discovered by Austria physicist Victor Hess, by recording electrometer readings
as a function of altitude; Nobel Prize 1936

Observation of Cosmic Rays



Energies ranging up to 10^{20} eV

Composition: mostly protons, but also nuclei up to Fe

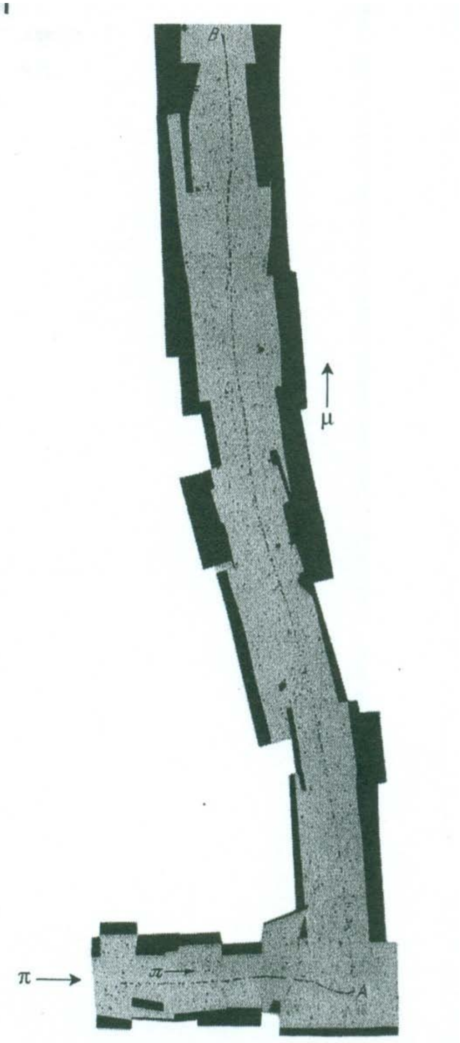
Is still a very active area of research: Astroparticle physics

Observations with Satellite-based and ground-based detectors; with telescopes observing the absorption in the atmosphere

From M. Jeitler

1947: Powell

Solving the ‘Meson’ puzzle: discovery of pion and muon



Pion enters from left, decays into μ and neutrino

Picture shows trace of particles left in photographic emulsion (still today the most technique for measuring tracks of particles !)

Nobel Prize 1950

Why do muons reach the surface of the Earth ?

- Atmospheric muons yield a nice illustration of the effect of **time dilatation** predicted by the special theory of relativity:
  - muons come from the decay of pions created in the high layers of the atmosphere by high-energy cosmic particles;
  - the muons’ life time is 2.2 μs;
  - during this time span, even light cannot go further than about 600 meters;
  - this shows that the muon’s “inner clock” is slowed down due to relativistic effects when it travels approximately at the speed of light

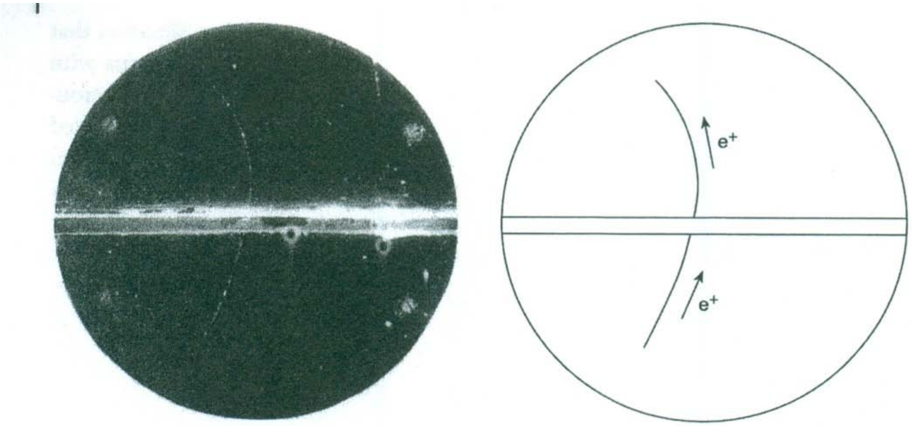
1930–1956: Antiparticles

1927: Dirac discribes relativistically free electron, energy E

- $E^2 - p^2 c^2 = m^2 c^4$
- $E = \pm (m^2 c^4 + p^2 c^2)^{1/2}$
- predicts ‘negative’ energy states
- Dirac’s way out: all negative energy states are filled with electrons; due to Pauli-principle all observable electrons correspond to positive energy states; absence of electron in negative sea are ‘holes’, positive particles, but not observed
- shared 1933 Nobel Prize with Erwin Schrödinger for ‘the discovery of new productive forms of atomic theory’

1931: Anderson’s discovery of positron

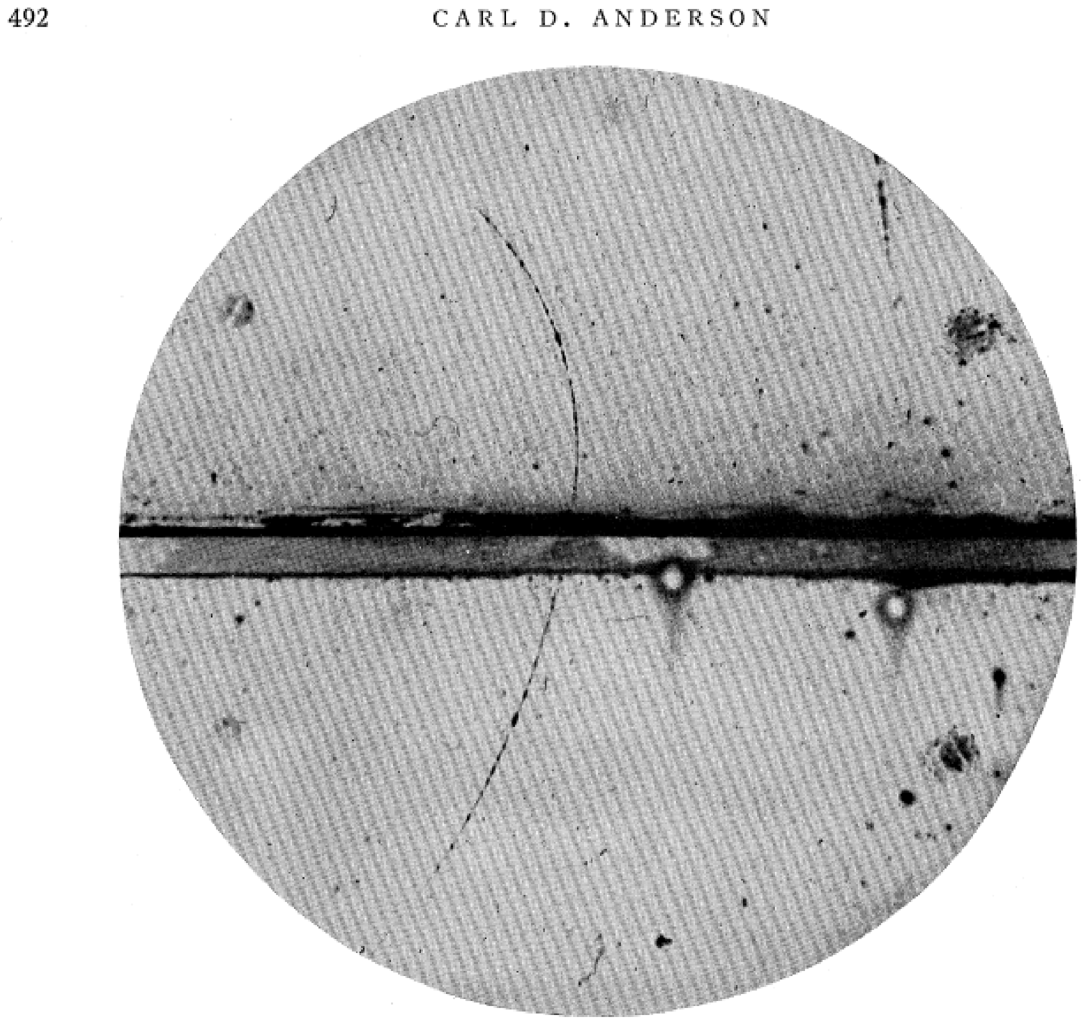
- Positron is positively charged twin of electron – antielectron
- Triumph for Dirac’s formalism



- track in cloud chamber, placed in magnetic field
- energy loss of particles in *Pb* – plate ⇒ particle moves upwards ⇒ positively charged
- Exercise: explain how Anderson estimated the mass of this particle

- Nobel Prize in 1936

1931: Anderson’s discovery of positron



492 CARL D. ANDERSON

1940s: Feynman, Stuckelberg

- Negative energy solutions are expressed as positive energy states of a different particle, positron

- Is a natural solution of Quantum Electrodynamics

- Is a profound feature of QFT
  - for every kind of particle its antiparticle must exist

1955: Discovery of Antiproton, $\overline{p}$

- Production and detection at Bevalac Accelerator, Berkeley
  - picture book case for particle discovery; will be discussed in ‘Detector’ Block

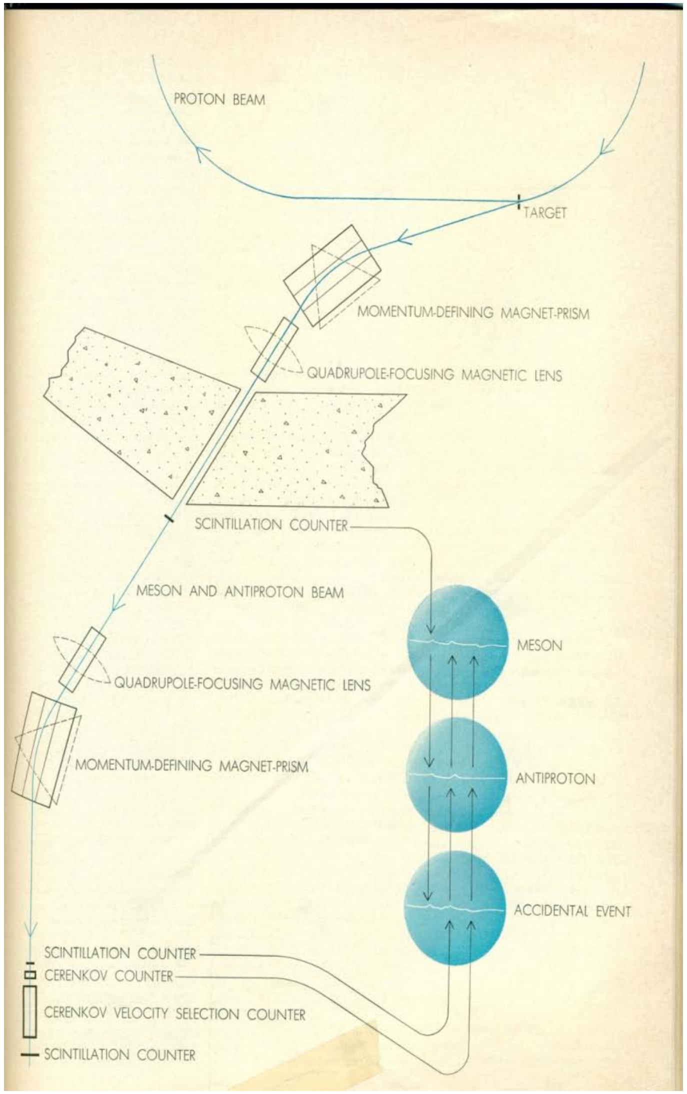
- 1956: Discovery of Antineutron, $\overline{n}$
  - besides charge, mass, spin and neutron carries
    - ‘baryon’ quantum number ($B(n) = 1$, $B(\overline{n}) = -1$)
    - has internal structure ⇒ dipole moment *d*; $\overline{n}$ has opposite *d*

- QFT gives a satisfying symmetry between matter and antimatter

- A very big question:
  - how did matter survive (and not completely annihilate with antimatter) in the Early Universe?
  - condition for forming stars, planets, LIFE

- E. Segre and O. Chamberlain received Nobel Prize in 1959

Antiproton Discovery



Sign of charge determined by magnetic deflection

Momentum measured by magetic deflection

Velocity measured by ‚Cherenkov' technique
(will be explained in Detector Block), which can discriminate between slow (antiproton) and fast (mesons)

1930 – today: Neutrinos, 80 years of surprises

1930: β – decay crisis

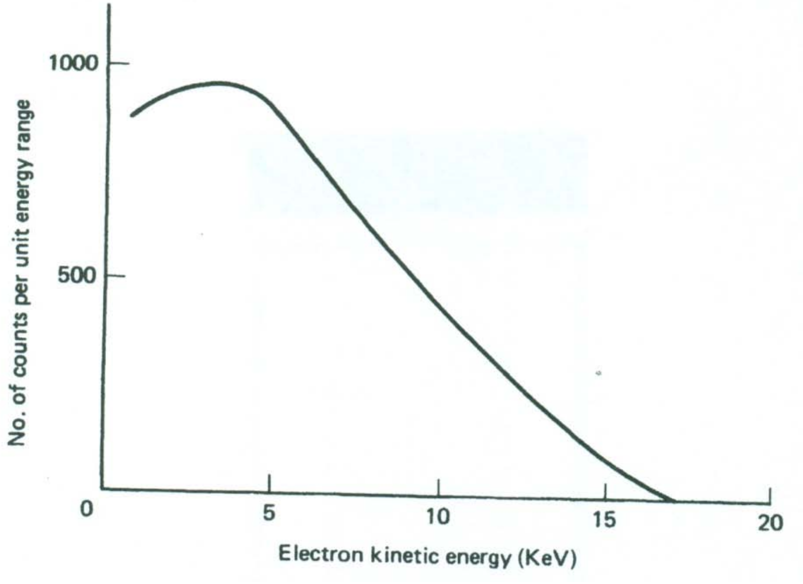
- radioactive nucleus *A* decays into slightly lighter nucleus B under emission of electron e^-
- conservation of charge: *B* is one unit more positive than *A*
- example: $^{3}H \rightarrow {}^{3}_{2}He,\ {}^{40}_{19}K \rightarrow {}^{40}_{20}Ca$
- in a two-body decay $A \rightarrow B + C$, outgoing energies are kinematically constrained

$$E(e) = (m_A^2 - m_B^2 + m_C^2)c^2 / 2m_A$$

  - o energy *E* of emitted electron is fixed
  - o experimentally: energy of electron varies from *0* to *E*

1930: β – Decay Crisis

- Very disturbing result with different attempts of explanation
  - Bohr: energy conservation is violated
  - Pauli: another ‘invisible’ particle emitted (‘neutron’)



  - electron spectrum emitted in β-decay of tritium

β – Decay: search for evidence of non-zero mass neutrinos

A next Generation Tritium Beta Decay Experiment 6

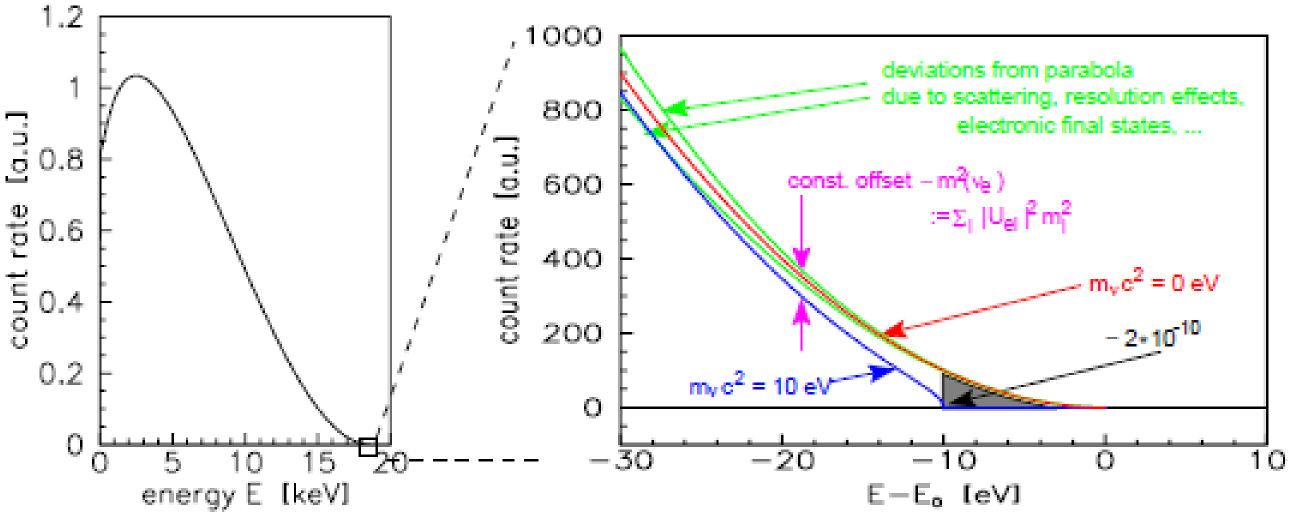


Figure 1. β electron spectrum of tritium β decay: complete (left) and interesting region around endpoint E_0 (right). The β spectrum is shown for arbitrary neutrino masses of 0 (red) and 10 eV/c^2 (blue), the green lines indicate modifications of the experimental spectrum due to scattering of β electrons in the tritium source, due to electronic final states (the ^{3}He$^+$ need not to be in the groundstate) and due to resolution effects.

β-Decay, continued

- 1932: Chadwick discovers neutral partner to proton – neutron

- 1933: Fermi develops theory of β-decay, incorporating Pauli's suggestion
  - very well consistent with experiments
  - energy spectrum of electrons reaches up to kinematically allowed limit ⇒

- Emitted particle must be very light
  - Fermi calls it neutrino
  - neutrinos were considered massless until the 1995 discovery and solution to another ~40 year long puzzle

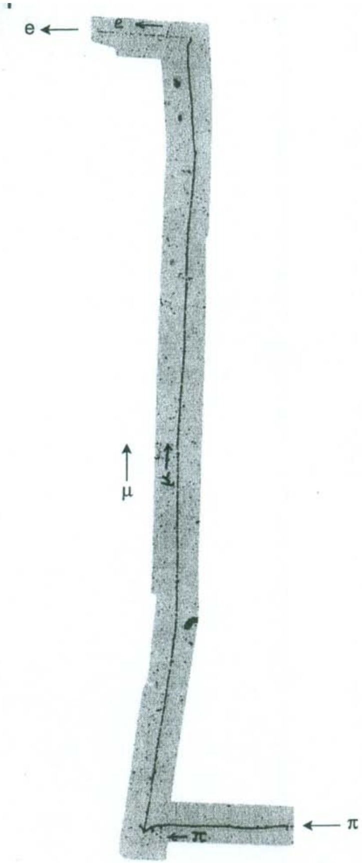
A Parenthesis: Anectotal comment on a great scientist, Niels Bohr

- 1912: W. Bohr suggests ‘planetary’ model of atom

- However, this most eminent scientist was not immune to poor physics judgment
    - outspoken critic on Einstein’s light quantum
    - mercilessly denounced Schrödinger’s equation
    - discouraged Dirac to work on the relativistic electron theory
    - opposed Pauli’s introduction of the neutrino
    - ridiculed Yukawa’s theory of the meson
    - criticized Feymann’s approach to quantum electrodynamics

Neutrinos: Pion and muon decay

- Pion decay: $\pi \rightarrow \mu + \nu$
- Muon decay: $\mu \rightarrow e + 2\nu$
- Exercise: how do we know that two neutrinos are emitted ?



Pion decaying into a muon plus neutrino;

The muon subsequently decays into an electron and two neutrinos

⇒ compelling theoretical evidence for neutrinos, but ….. need to experimentally check this hypothesis

1953: Cowan and Reines discover neutrinos

- Neutrino source: powerful nuclear reactor
- Detector: large water tank
- Reaction studied: inverse β-decay $\bar{\nu} + p \rightarrow n + e^{+}$ from U-fission in Nuclear Reactor
- Cross section: $\sigma(\bar{\nu} + p \rightarrow e^{+} + n) \approx 10^{-43} E^{2} cm^{-2}$
- Flux of antineutrinos (calculated) $F \sim 5x10^{13} s^{-1} cm^{-2}$
  - Problem: estimate the number of detected neutrinos/ day
- Detection of positron
- Method became crucial in checking the solar model of fusion process
- A 42-year dramatic saga which culminated in
  - 1994: dramatic new insight into nature of ν's
  - 1995: Nobel prize for Reines (Cowan was already dead)

Cowan, Reines Experiment of Neutrino Discovery

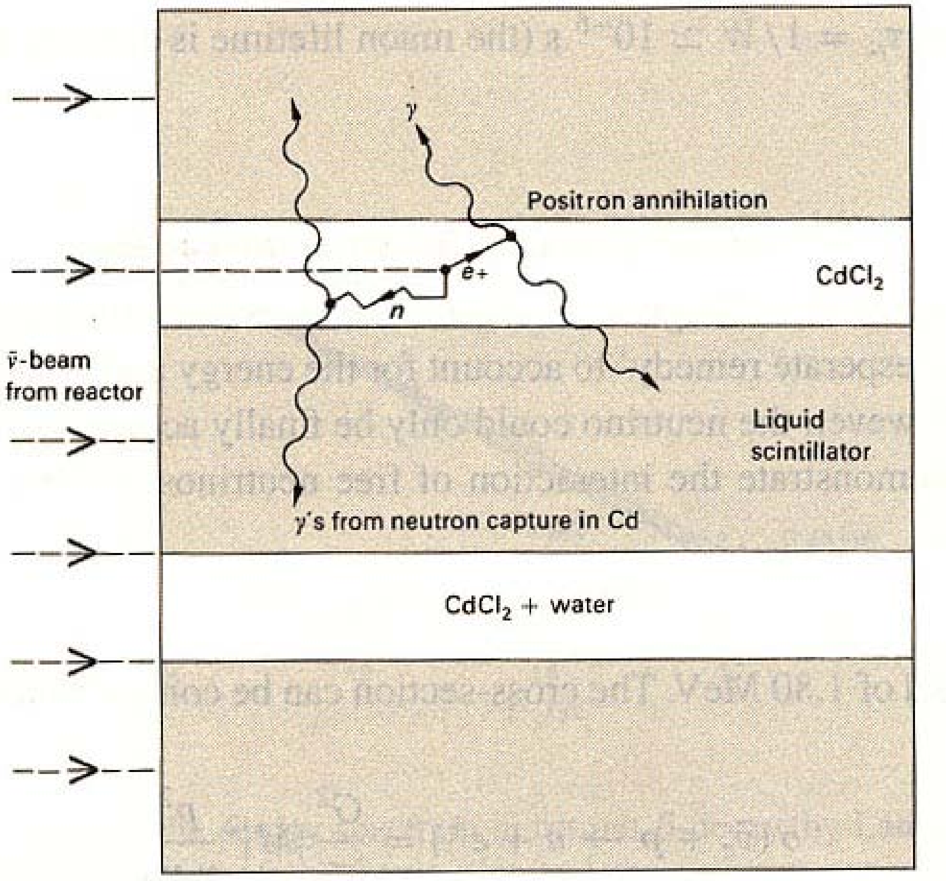
ν absorbed in water (200 l)with $CdCl_2$ (40 kg) dissolved in it, e^+ annihilated with e^- ⇒ producing

2 γ/s with 511 keV ⇒ Compton electron predicted in scintillators, viewed by 100 photomultipliers;

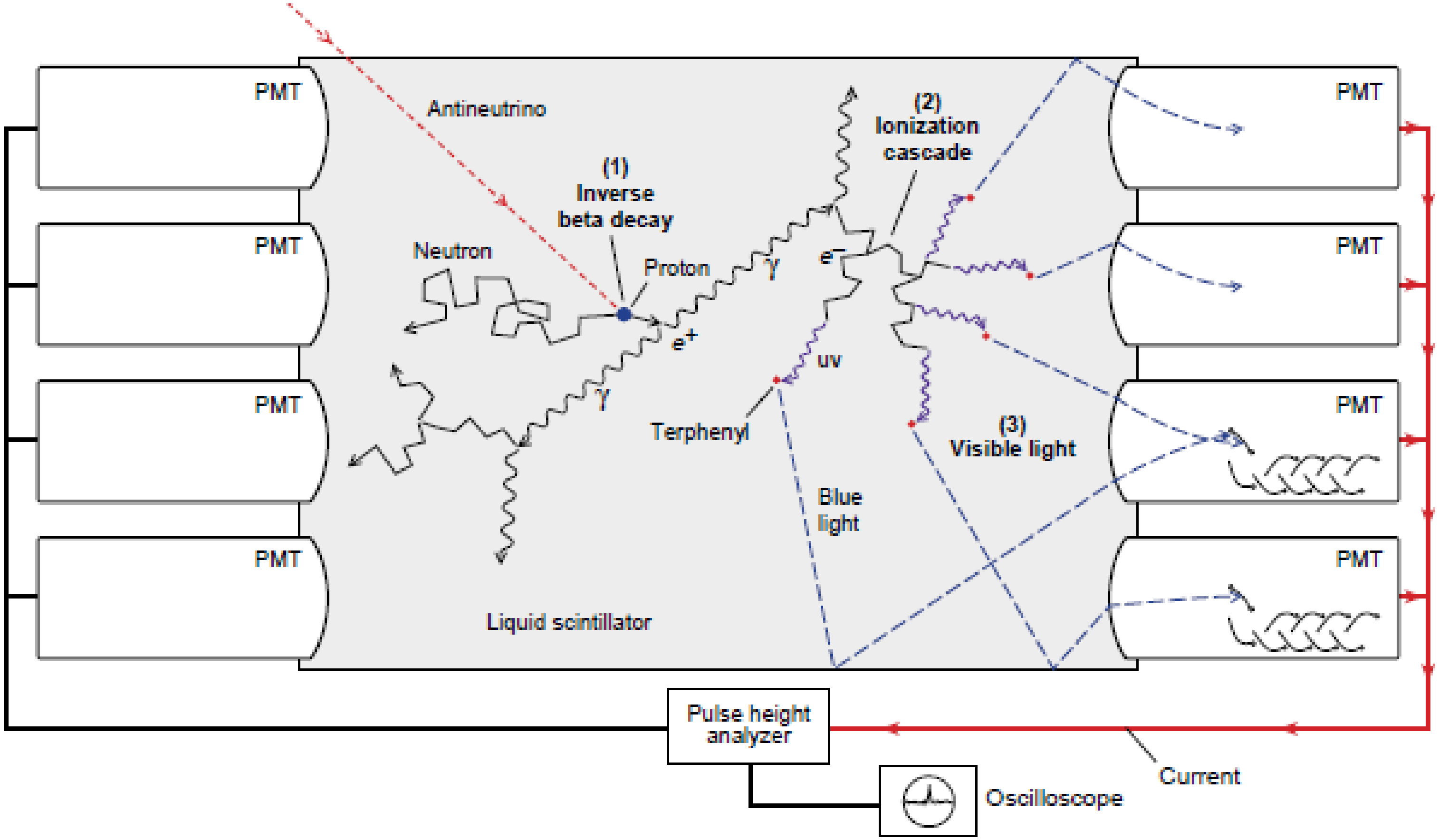
n slowed down and captured in Cd, few μs later; (Cd has a very large capture crosssection for neutrons)

N + ^{108}Cd -> ^{109}Cd + γ

Signature: prompt pulse from annihilation and delayed pulse from *n*-capture



Cowan, Reines Experiment of Neutrino Discovery



Detecting the positron from inverse β-decay through coincident scintillation flashes

Neutrinos: Lepton number

- Cowan, Reines: $\overline{\nu} + p \rightarrow e^{+} + n$ is observed
- Davis: $\overline{\nu} + n \rightarrow p^{+} + e^{-}$ is NOT observed

  Forbidden due to conservation of a quantum number

  - Lepton number *L* is conserved

$$e, \mu^{-}, \nu \quad L = +1$$

$$e^{+}, \mu^{+}, \overline{\nu} \quad L = -1$$

$$\pi^{-} \rightarrow \mu^{-} + \overline{\nu}; \quad \pi^{+} \rightarrow \mu^{+} + \nu$$

$$\mu^{-} \rightarrow e^{-} + \nu + \overline{\nu}; \quad \mu^{+} \rightarrow e^{+} + \nu + \overline{\nu}$$

Neutrinos: There is much more to it …

- $\mu^- \to e^- + \gamma$ not observed, although charge and Lepton numbers are conserved

- Why ? ⇒ famous rule of thumb (Feynman):
  - whatever is not expressively forbidden, is mandatory (in physics)

- Absence of $\mu^- \to e^- + \gamma$ ⇒ conservation of ‘muon-ness’
  - but $\mu \to e + \nu + \overline{\nu}$

- Perhaps: two kinds of neutrinos ?
  - one associated with $e \to \nu_e \quad (L_e = +1)$
  - one associated with $\mu \to \nu_\mu \quad (L_\mu = +1)$

Neutrinos: There is much more to it …

- Answer: conservation of electron number and muon number

$$n \rightarrow p^{+} + e^{-} + \overline{\nu}_{e}$$

$$\pi^{-} \rightarrow \mu^{-} + \overline{\nu}_{\mu}; \quad \pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\mu^{-} \rightarrow e^{-} + \overline{\nu}_{e} + \nu_{\mu}; \quad \mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

1962: Experimental Test of Two-Neutrino Hypothesis

- Lederman, Schwartz, Steinberger + collaborators
  - $\sim 10^{14}$ antineutrinos from π^- - decay $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
  - observed 29 events of the reaction

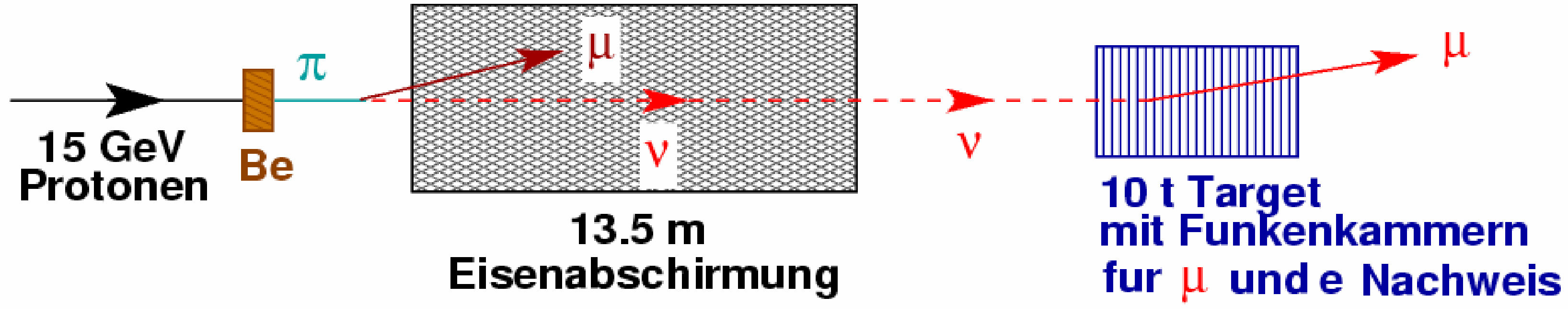
$$\bar{\nu}_\mu + p^+ \rightarrow \mu^+ + n$$

  - no events of forbidden reaction

$$\bar{\nu}_\mu + p^+ \rightarrow e^+ + n$$

- 1985: Nobel Prize awarded to Lederman, Schwartz, Steinberger

Experimental verification of the Two-Neutrino Hypothesis



15 GeV
Protonen

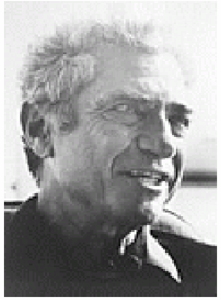
Be

13.5 m
Eisenabschirmung

10 t Target
mit Funkenkammern
fur μ und e Nachweis

Lederman

Schwartz

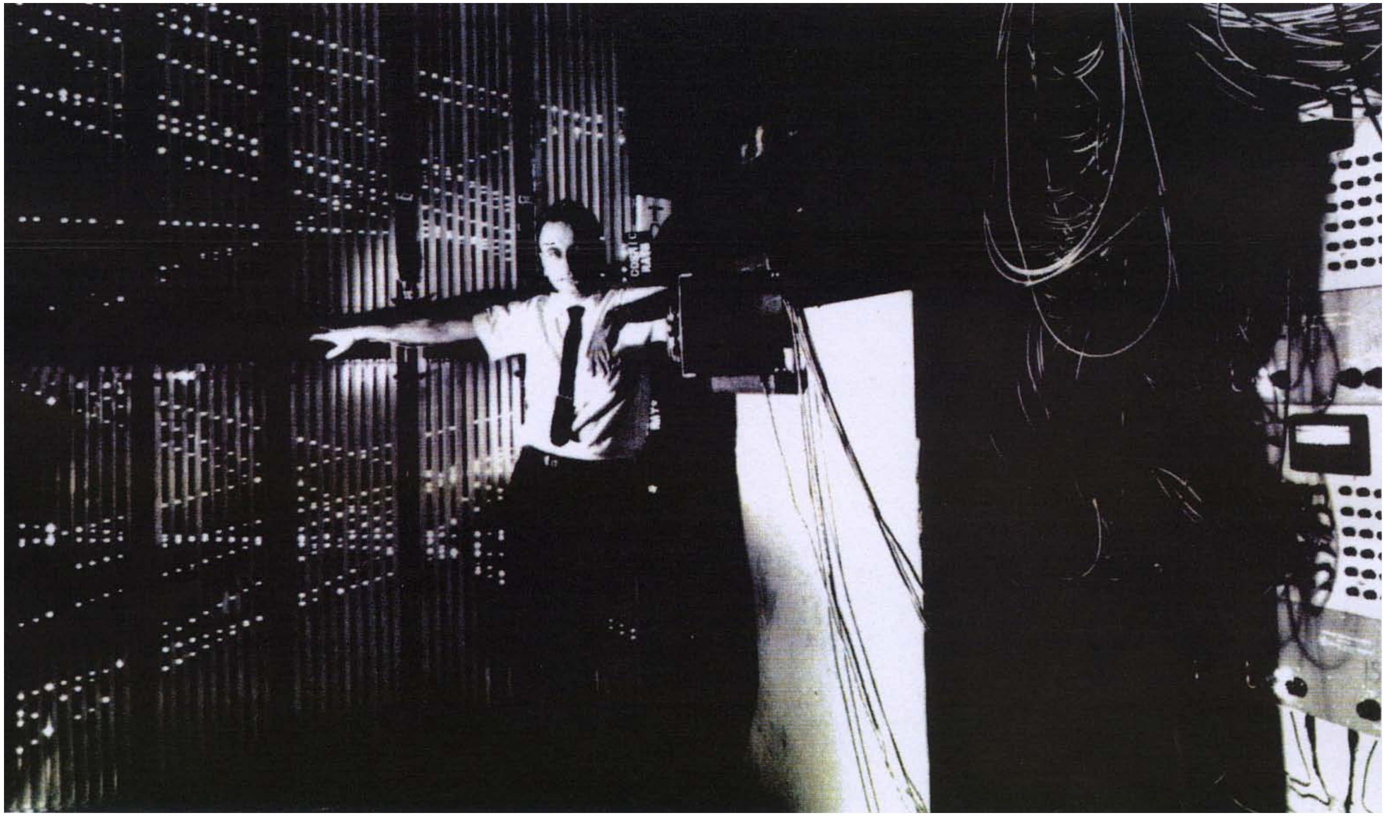


Steinberger

Nobelpreis 1988

for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino

Two-Neutrino Hypothesis Experiment at BNL



M. Schwartz near apparatus to detect muons in Spark Chambers; signals were recorded photographically

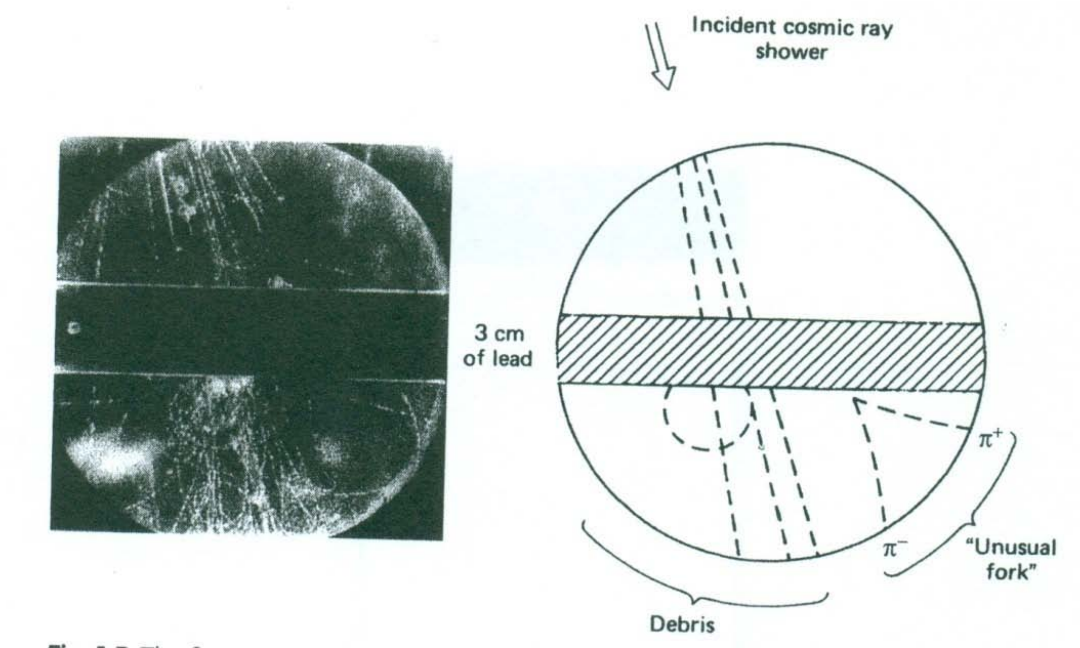
1962-1976: Status of Lepton Families

		Electron number	Muon number
Leptons	e^-	1	0
	ν_e	1	0
	μ^-	0	1
	ν_μ	0	1
Antileptons	e^+	-1	0
	$\bar{\nu}_e$	-1	0
	μ^+	0	-1
	$\bar{\nu}_\mu$	0	-1

1947-1960: ‘Strange’ Particles: New perspectives

- 1947: $p, n, e^{-}, \mu, \pi, 0$ and antiparticles:
  - muon presented a puzzle; Rabi: who ordered that ?
  - a simple, pleasing and satisfactory view of the world
  - job of particle physics appeared to be essentially done

- But in December of 1947: Cosmic ray particles striking a lead plate



producing

$$K^0 \rightarrow \pi^+\pi^-$$

new neutral particle with al least twice the mass of a pion

1947–1960: More Mesons and Baryons

- In addition to $K^0, \ldots \eta, \phi, \omega, \varphi \ldots\ldots$ meson family
- In addition to *p*: $\Lambda \to p^+ + \pi^-$

  $p \to e^+ + \gamma$ not observed: *p* is stable

  - Stueckelberg: Baryon number conservation

- By 1960: ‘Zoo’ of particles: living in the jungle of particle physics
- 1955: Lamb in his Nobel Prize speech:
  - a deluge of other ‘elementary’ particles appeared after 1930 ……I have heard it said that “a finder of a new elementary particle used to be rewarded by a Nobel Prize …. but such a discovery now ought to be punished by a 10 000 $ fine !”

Why are they called ‘Strange’ Particles ?

- Strange Particles
  - produced abundantly in particle collisions at time scale of 10^{-23} sec
  - decay slowly, typically at time scale of ~10^{-10} sec (very long, i.e. ***very strange***)

- Pais et al. : production mechanism differ from decay mechanism
  - produced by strong force (nuclear force)
  - decay via weak force (such as β-decay)

- 1953: Gell-Mann and Nishijima assigned a new property
  - ‘Strangeness’: new property (= new quantum number) conserved in Strong Interactions, but ***not*** conserved in Weak Interactions

Why ‘Strange’ Particles ?

- Production in pairs (strangeness is conserved in hadronic interaction)

$$\pi^- + p \to K^+ + \Sigma; \quad \to K^0 + \Sigma^0; \quad K^0 : S = +1$$

$$K : S = 1; \quad \Sigma, \Lambda : S = -1; \quad \pi, p, n, .. : S = 0$$

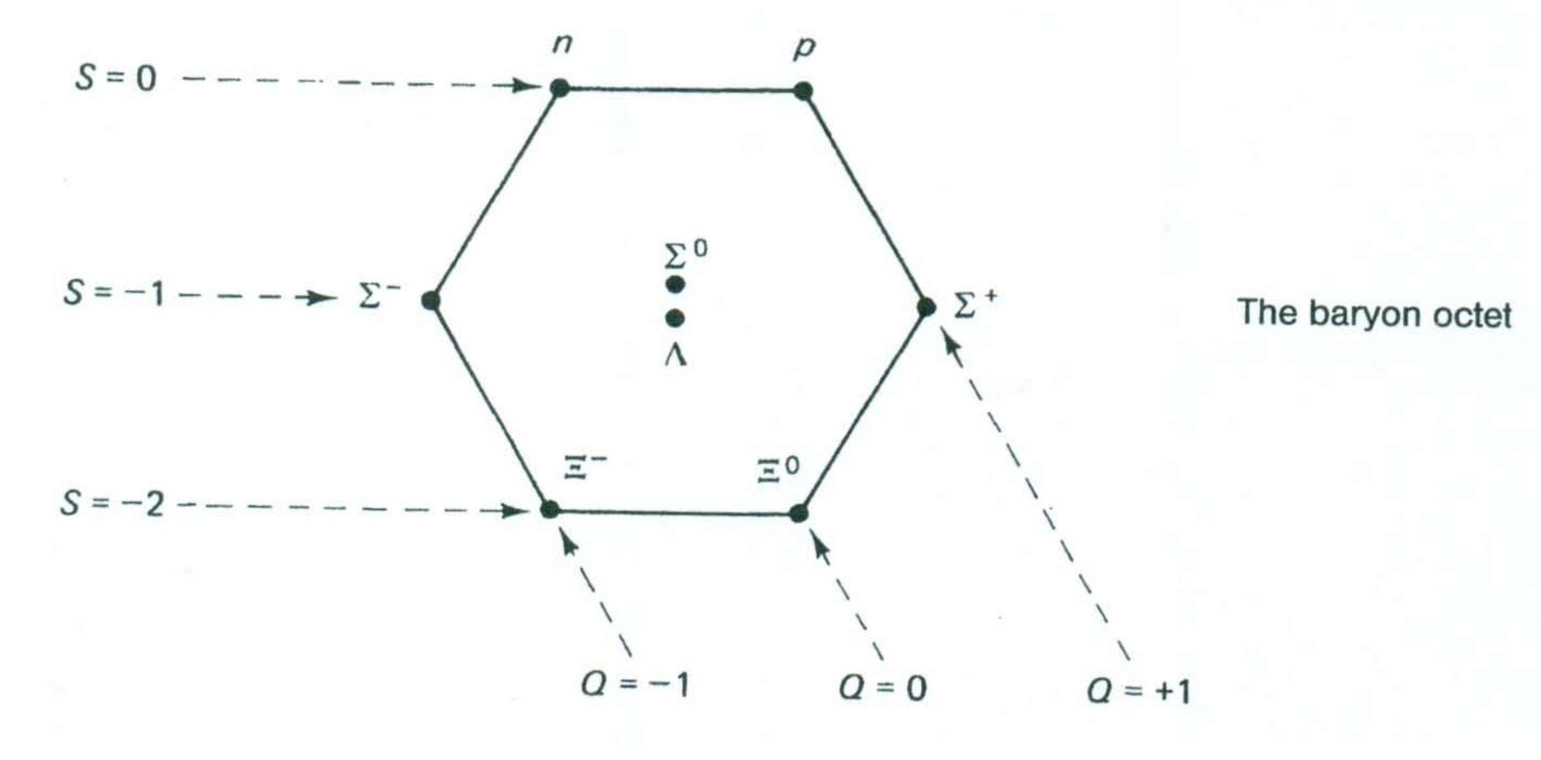
- Decay via weak interaction violates strangeness conservation

$$\Lambda \to p^+ + \pi^- ; \Sigma^+ \to p^+ + \pi^0$$

- Weak processes do not conserve Strangeness
- Pre-1960: a plethora of hadrons (baryons and mesons) distinguished by charge, mass, strangeness… without any guiding principle: similar to chemistry 100 years earlier, prior to the ‘Periodic System of the Elements’.
- Particle Physics was waiting for ‘its’ periodic system

1961-1964: The Eightfold Way*: The first periodic table of particle physics

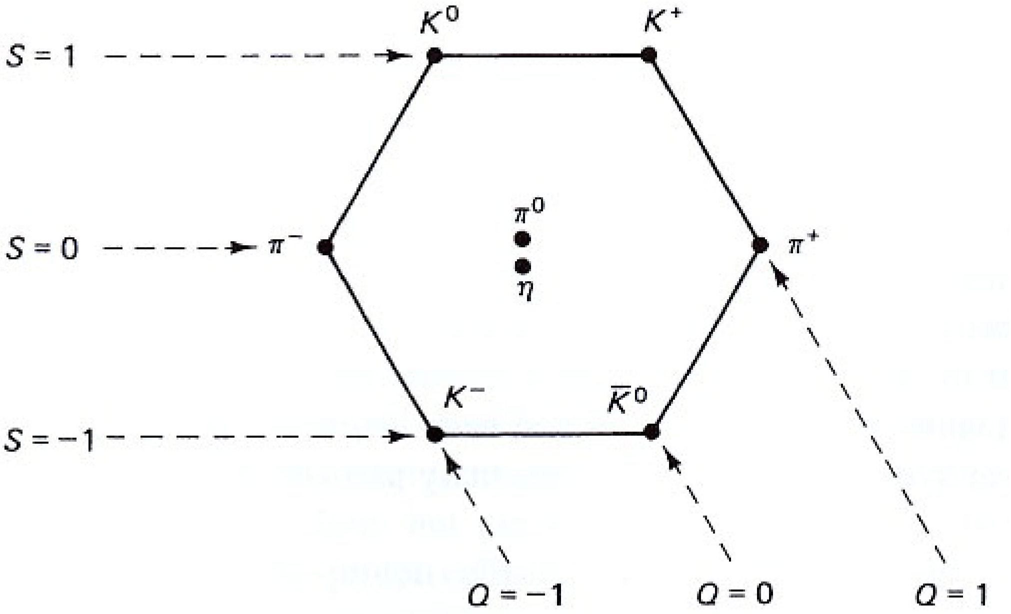
- 1961: Gell-Mann (and Y. Ne’eman) introduce a classification



- *Alluding to Buddhism: Noble Eightfold Path: is the way to develop insight into the true Nature of phenomena

The Eightfold Way: Meson octet

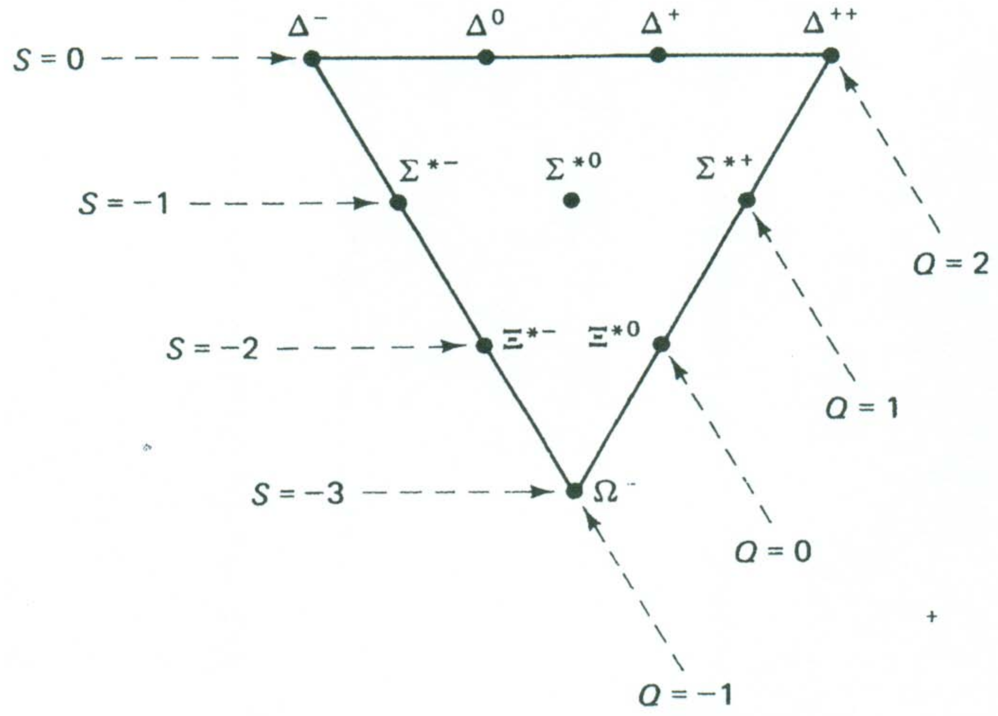
In a similar way: the lightest mesons fill also an hexagonal array, Forming the meson octet



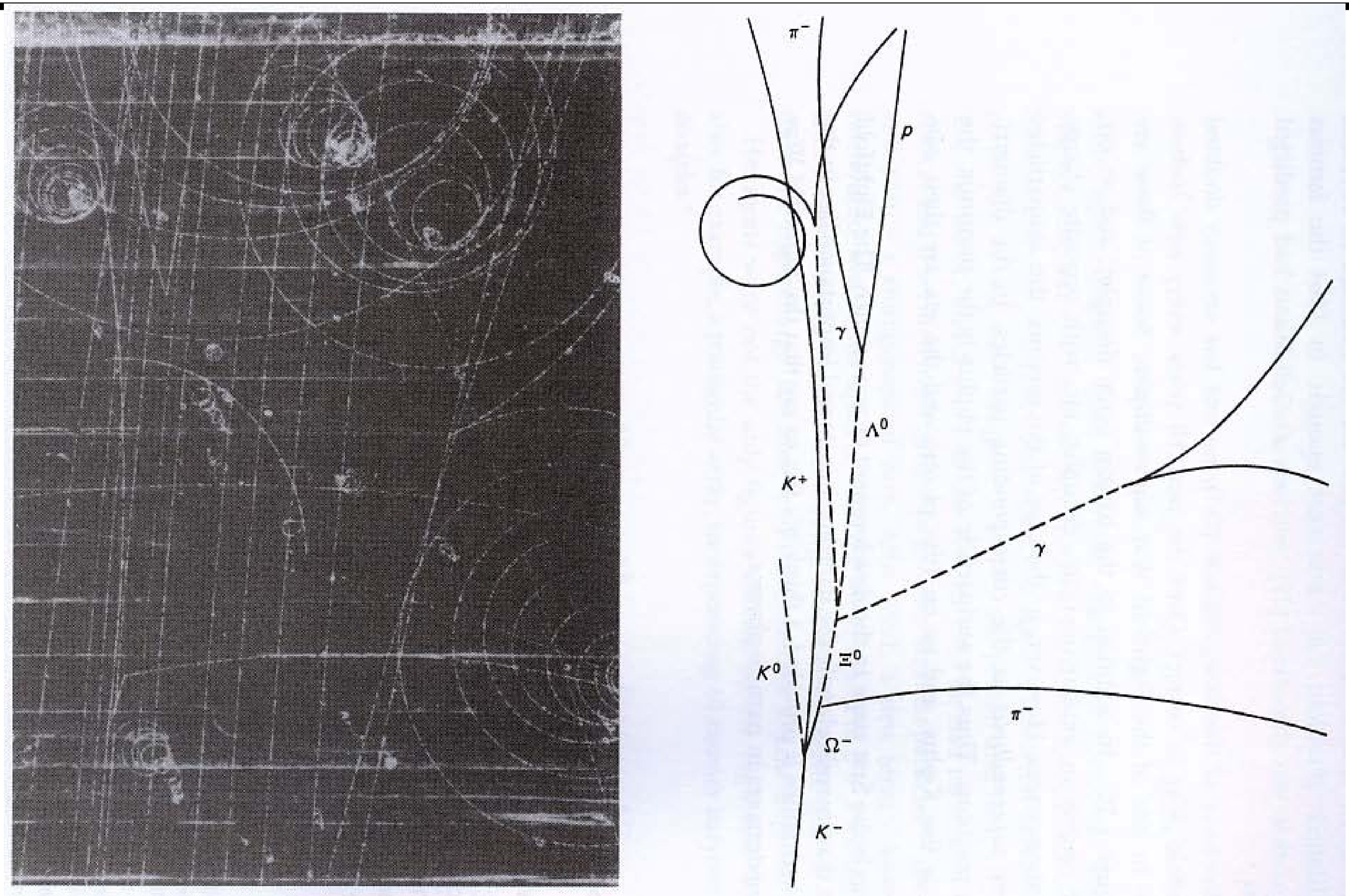
The Eightfold Way: Baryon decuplet

In addition to Hexagons there are also other patterns for the assignment, e.g. the triangular array to organize 10 heavier baryons

A beautiful vindication of this model: nine of the 10 particles were known Ω^- was not known; Gell-Mann proposed how to produce it; estimated lifetime and mass observed in 1964



Ω^-: A triumpf of the Eightfold Way



Bubble Chamber Photograph and line diagram of the relevant tracks

The Eightfold Way: More than a classification scheme

- Provided a classification: all particles observed fell into one of the (Super) multiplets

- Provided organizational structure
- Asking ‘Why do hadrons fir into these bizarre patterns’ provided basis for
  - 1964: begin of modern particle physics
  - Gell-Mann, and, independently, Zweig, proposed:

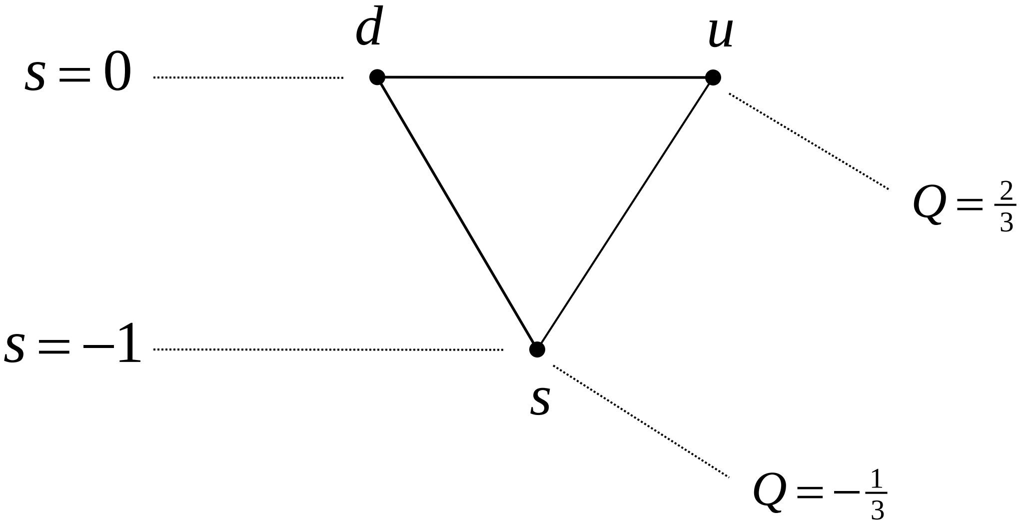
- All hadrons are composed of more fundamental constituents

- Quarks: name given by Gell-Mann
  - from J. Joyce: Finnigans Wake: ‘Three Quarks for Muster Mark’

Essentials of the Quark Model I (1964)

- 1964: Quarks exist in three types: ‘Flavors’
  - *u* (‘up’) ; *d* (‘down’) ; *s* (‘strange’)

- These three flavors form a triangular ‘Eightfold Way’

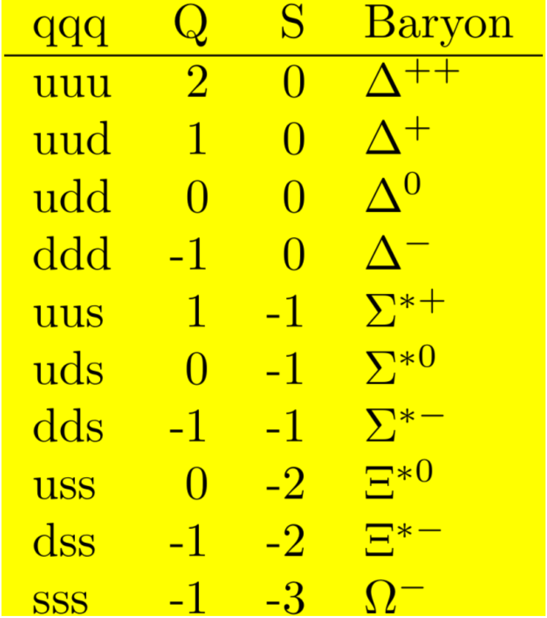


- To each quark corresponds an antiquark with opposite charge and strangeness

Essentials of the Quark Model II (1964)

- Two composition rules
  - every baryon is composed of three quarks (every antibaryon of three antiquarks)
  - every meson is composed of a quark and an antiquark

- Example: Baryon Decuplet



qqq	Q	S	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^{+}
udd	0	0	Δ^{0}
ddd	-1	0	Δ^{-}
uus	1	-1	Σ^{*+}
uds	0	-1	Σ^{*0}
dds	-1	-1	Σ^{*-}
uss	0	-2	Ξ^{*0}
dss	-1	-2	Ξ^{*-}
sss	-1	-3	Ω^{-}

The Quark Model III

- All the Supermultiplets can be constructed naturally in the Quark Model

- Same set of quarks can form different states (particles)
  - proton : *uud* ; Δ^+ : *uud*
  - considered as two particles, because difference (masses) ~ mass
  - in contrast to *H*-atom: restmass ~10^9 eV, excited levels ~1eV

- Certain states can never be formed:
  - baryon with $S = 1$ and $Q = -2$ not possible in Quark Model
  - Searches for such ‘exotic’ states were all negative

The Quark Model V

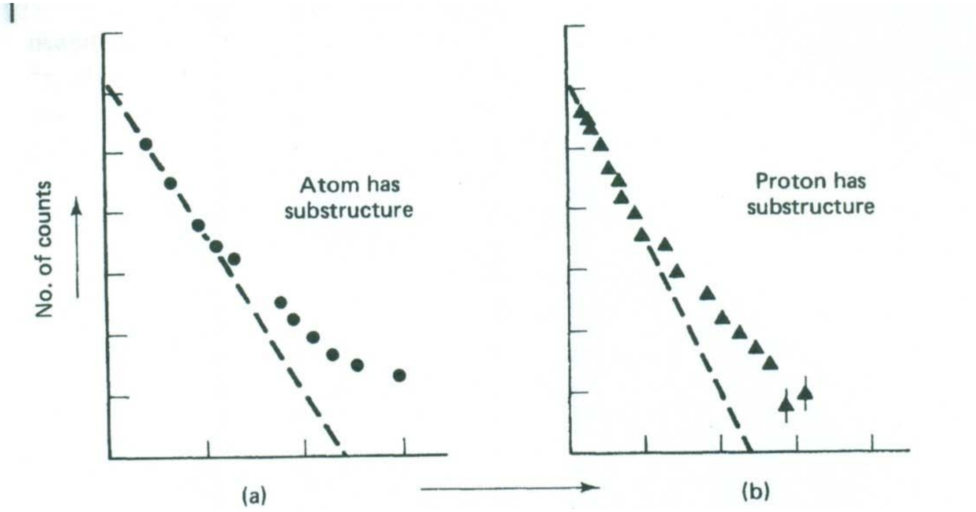
- Fundamental issue: search for free quarks
  - quarks should be easily produced, e.g. by hitting a proton in an energetic collision
  - easily detectable due to fractional charge
  - at least one quark should be stable
  - ~ approximately 15 years of many dedicated experiments produced no evidence for free quarks

Quark Model VI: From problem to paradigm

- New paradigm: free quarks cannot exist
  - major input and basic ingredient to theory of strong interactions: Quantum Chromodynamics
  - ‘quark confinement’: the precise mechanism is still a very active research topic

- Experimental indication:
  - probing the internal structure with an energetic probe
    - conceptually similar to Rutherford scattering experiment
    - electrons; muons; neutrinos; protons

Probing the Composite Structure of the Nucleon



- Rutherford scattering: number of particles deflected through large angle indicates that atom has an internal structure
- Deep inelastic scattering: number of particles deflected through large angle indicates that proton has internal structure (Feynman calls these particles ‘partons’; are these partons the quarks of Gell-Mann ?
- Indication for three ‘lumps’
- 1990: Friedman, Kendall and Taylor awarded Nobel Prize

Quark Model VII: One more new ingredient

- Quark Model appears to violate Pauli Exclusion Principle
  - no two half-integer spin particles can occupy the same status
  - quarks have S = ½
  - proton is made from *u, u, d*; Δ^{++} : *u, u, u*
  - 1964: Greenberg suggests that quarks have additional quantum number: ‘COLOR’ (a term to denote an additional property)
    - Quarks come in three ‘colors’, arbitrarily ‘painted’ ‘red’; ‘green’; ‘blue’ [not a color, but a label]
  - baryons are made from quarks of different color

- Met with considerable skepticism: another trick to save the quark model ? Turned out to be
- **Final ingredient to the formulation of the theory of Strong Interactions, Quantum Chromodynamics!**

Quark Model VIII: Color

- Color-concept (a nicely chosen label) implies:

- All naturally occuring particles are ‘colorless’

- Colorless:
  - total amount of color is zero
    - ex.: mesons are made of $q\overline{q}$
  - all three ‘colors’ are represented in equal amounts (suggestive analogy: the three primary colors in a light beam combine to white light)

1974-1995: Experiments Establishing the Quark Concept

- 1964-1974: eventless period for particle physics
  - quark model, despite some success, generally met with scepticism (no free quarks, color ?)

- November 1974 Revolution made the decisive change in ‘culture’
  - discovery of the particle J/ψ
  - S. Ting and collaborators observed a particle, $J \to e^+e^-$, produced in *p Be* collisions at BNL in the summer of 1974
  - weekend of Nov. 10-11, 1974: particle (same mass) discovered at SLAC is $e^+e^- \to \psi$ by B. Richter and collaborators

- Published simultaneously: referred to as the **J/ψ**

- 1976: B. Richter and S. Ting awarded Nobel Prize

J/ψ The Experimental Evidence

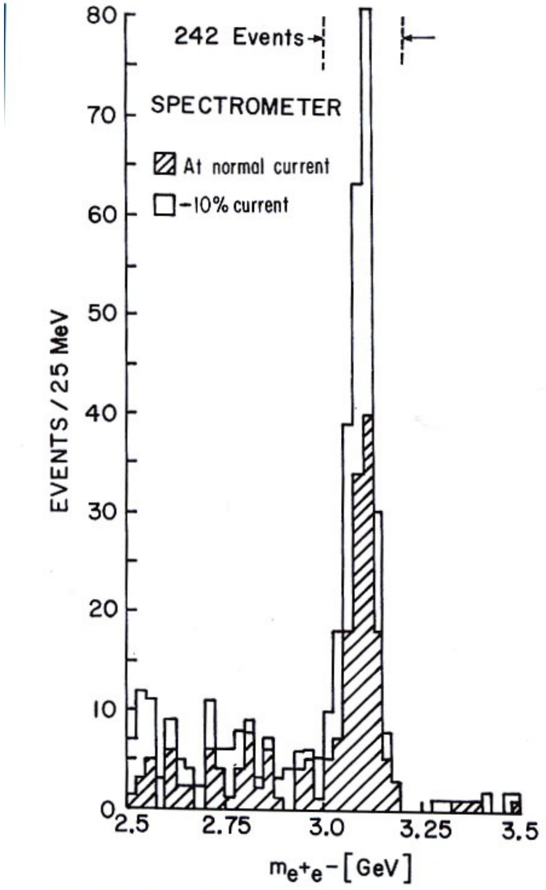


FIG. 2. Mass spectrum showing the existence of *J*. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

BNL

P + Be -> J + X

J -> $e^+ + e^-$

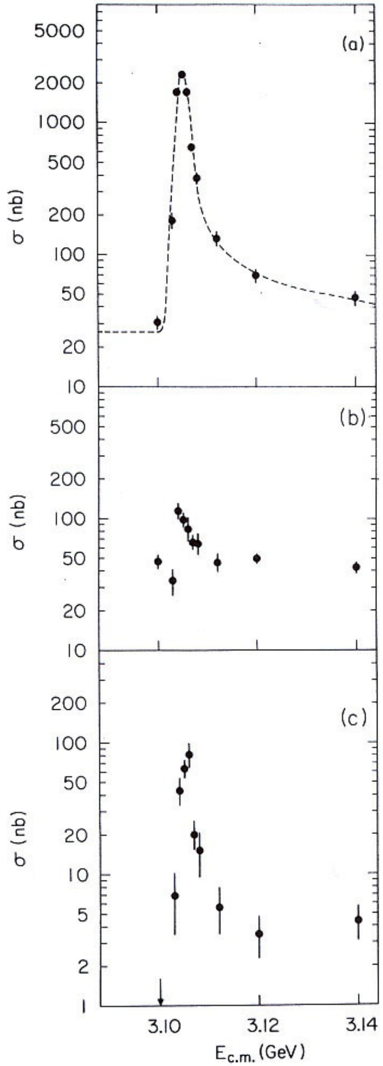
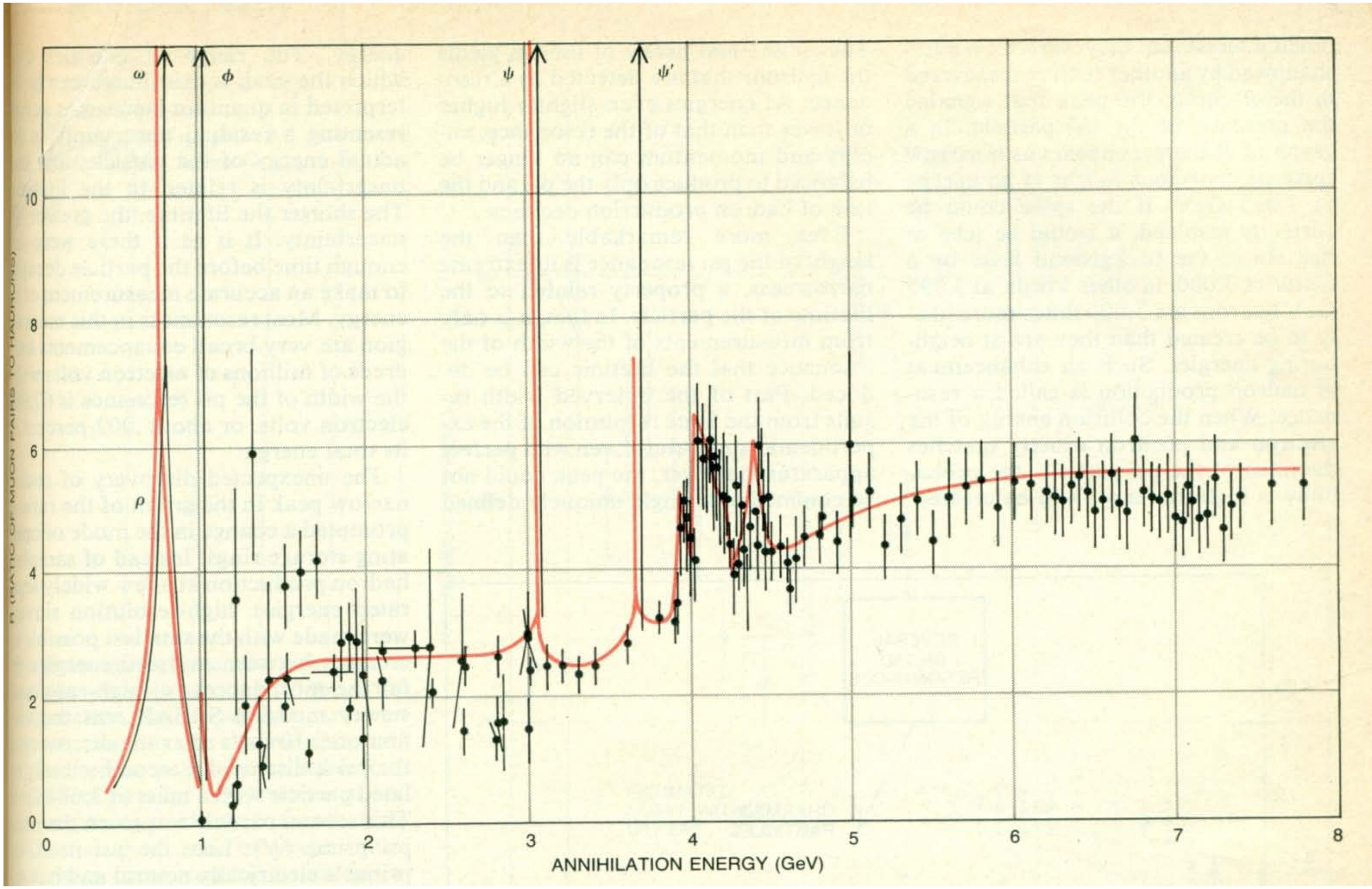


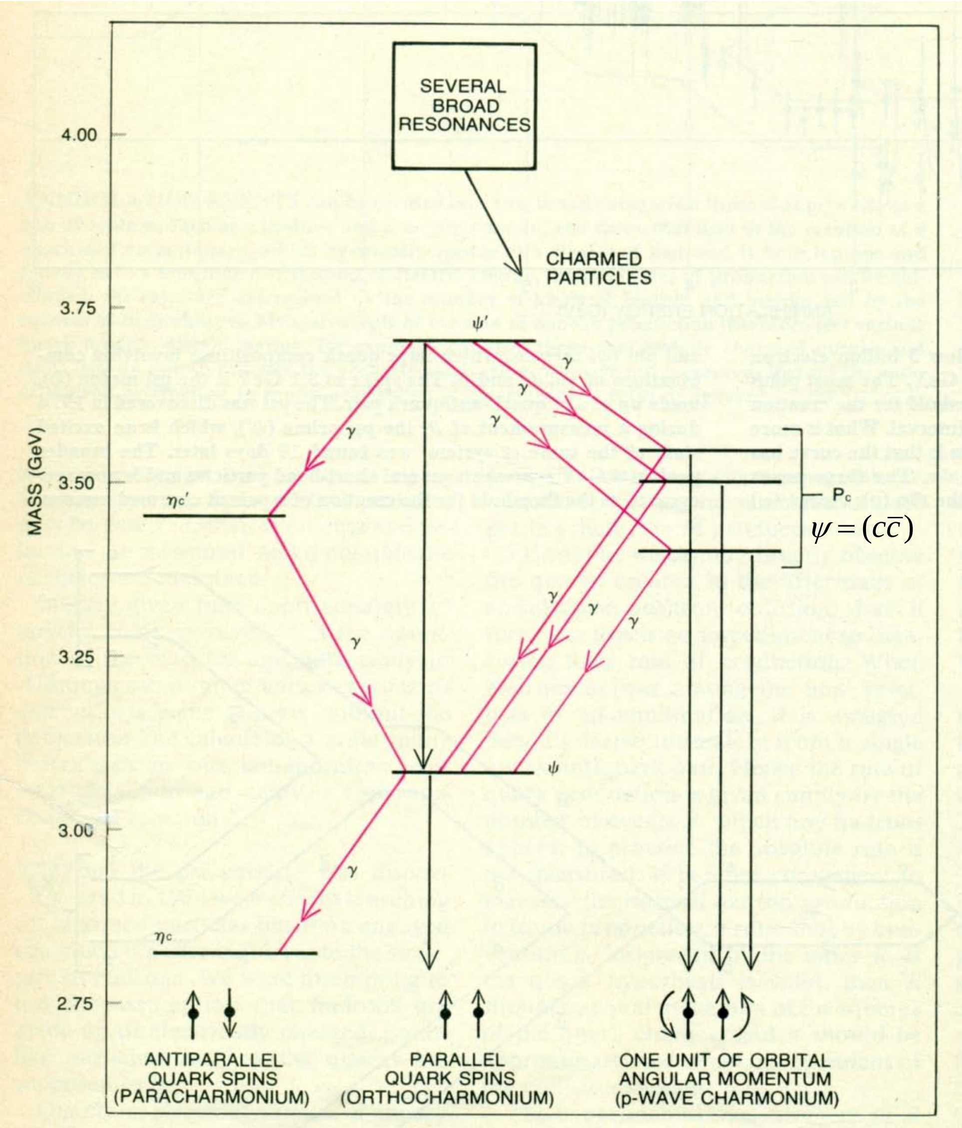
FIG. 1. Cross section versus energy for (a) multihadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

SLAC:
Electron-Positron Collider
Team leader
B. Richter

Electro-Positron collision porbabiity vs. energy



Charmonium (c cbar) system
the hydrogen of quarks



Exercise;

Estimate the lifetime of the J/ ψ particle- see previous diagram

(Hint: remember the uncertainty relation)

Why is your estimate an upper limit ?

J/ψ: A quantum leap in understanding

- *J/ψ*
  - extremely heavy meson: $M(J/\psi) \approx$ 3.1 GeV/c^2, more than three times as heavy as the proton (meson ↔ baryon !)
  - long lifetime: $\tau \sim 10^{-20}$ sec, compared to typical hadronic lifetime of 10^{-23}
    - o Exercise: explain, how this lifetime was estimated
  - this very long lifetime indicated new physics

- Nature of *J/ψ*
  - lively debate for several months
  - the quark model won: a fourth quark: charm (c)

$$\psi = (c\bar{c})$$

  -

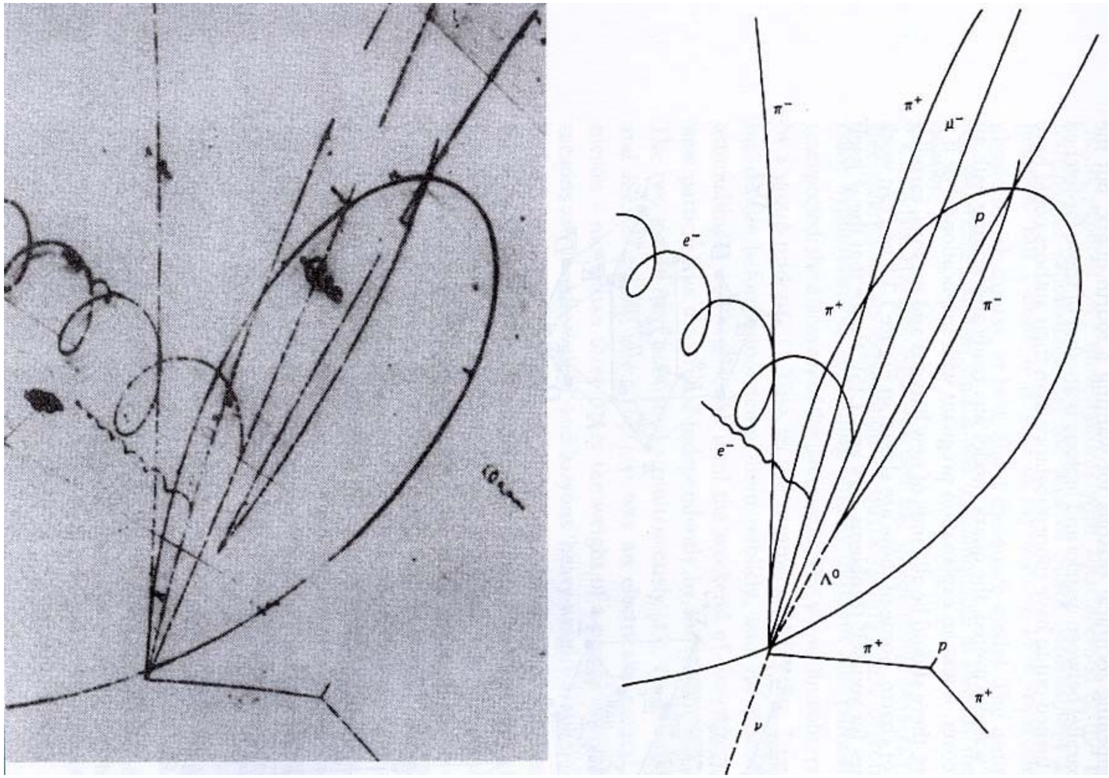
J/ψ: A quantum leap in understanding

- Lepton-Quark Parallel
  - leptons: e, ν_e, μ, ν_μ
  - quarks: $d, u, s, \quad ?$ $\qquad ? = c$

Charm: Hidden and naked

- $J/\psi = c\bar{c}$; if c is assigned ‘charm’ of $c + 1$
  - J/ψ has charm ‘hidden’
- Confirmation of quark hypothesis ⇒ particles with ‘open’ charm

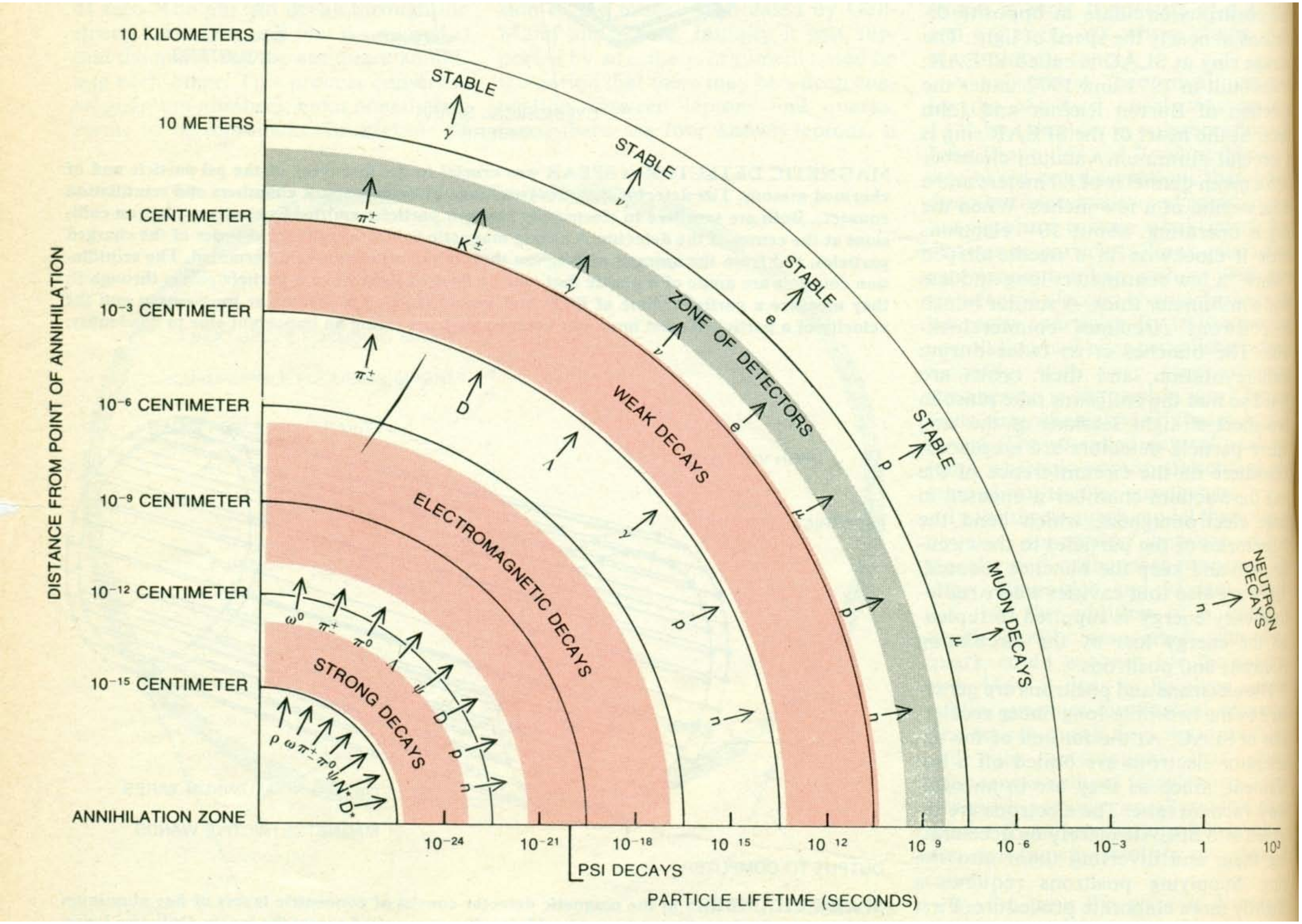
Discovery of open Charm: Λ_c



$$\nu_\mu + p \rightarrow \Lambda_c^+ + \mu^- + \pi^+ + \pi^-$$

$$\Lambda_c^+ \rightarrow \Lambda_0 \rightarrow p + \pi^-$$

Overview: typical particle lifetimes



1975: The Quark-Lepton Story continues

- 1975: Discovery of a new lepton (τ) by M. Perl and collaborators
  - M. Perl awarded Nobel Prize in 1995
  - for a brief moment quark-lepton symmetry was spoiled

- 1976: New very heavy meson discovered at FNAL by L. Lederman and collaborators and confirmed at CERN (Nobel Prize 1988)
  - upsilon $\Upsilon = b\bar{b},\ M \approx 6.1\, GeV/c^2$
  - a fifth quark, beauty
  - meson with open *b* found in 1982
  - B^0 mesons exhibit CP violation ⇒ *B*-factories
  - There must be a sixth quark

- 1995: Discovery of sixth quark, top, *t* announced at FNAL
  - Mass (*t*) = 174 GeV/c^2

1967-1983: Weak Interactions Revisited

- 1933: Fermi develops theory of weak interactions, valid for low-energy applications
  - Known to fail at high energies

- Theory needed in which interaction is mediated be exchange of some particle
  - ‘Intermediate Vector Boson’ (IVB)
  - what is the mass of IVB? related to range of Weak Interaction
  - What is the range of W.I.: no obvious scale available

- 1967: Glashow, Weinberg, Salam develop theory of electroweak interactions
  - unified treatment of electromagnetic and weak interaction

Electroweak Theory

- Theory has 4 mediators of electroweak force (‘gauge bosons’)
  - Photon $\gamma\,(m \approx 0)$
  - three heavy IVB’s
    - $M_{W^\pm} = 80.398 \pm 0.025\,GeV$
    - $M_{Z^0} = 91.1876 \pm 0.0021\,GeV$
    - $\sin\theta_W$ is parameter in theory which can be measured indipendently

- EW Theory predicts
  - $M_W = 82 \pm 2\,GeV/c^2$
  - $M_t = 92 \pm 2\,GeV/c^2$

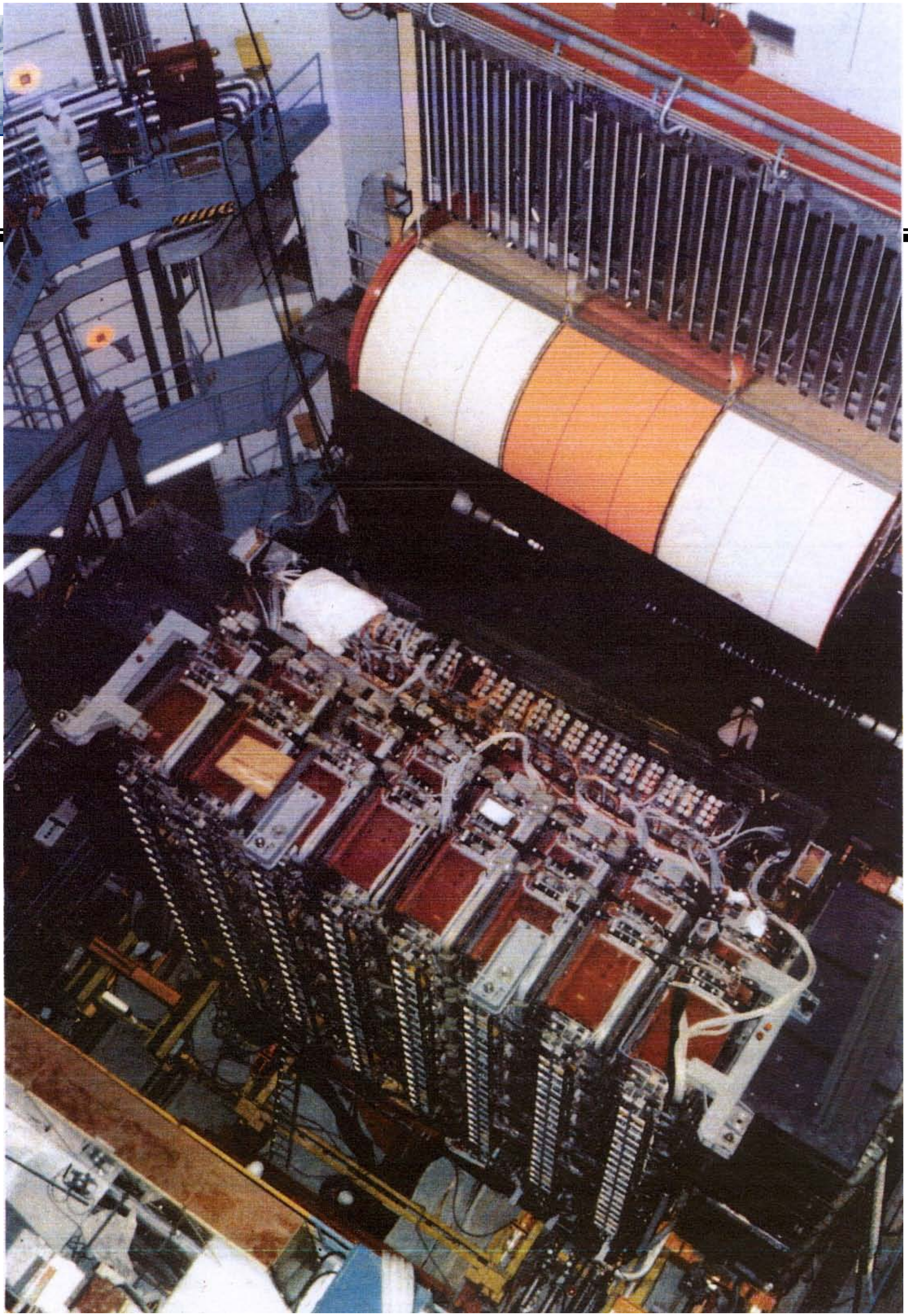
1983: Discovery of $W^{\pm}, Z^{0}$ at CERN

- 1976: D. Cline and C.Rubbia propose to convert SPS accelerator into $p\overline{p}$ collider
  - race with Fermilab develops which is building a $p\overline{p}$ collider
  - two experiments are being prepared by Rubbia-team, in which HEPHY participated, and by Darriulat-team
  - brilliant physical, technical, organizational acchievements

- 1983: discovery of *W* and *Z* announced

- 1984: Nobel Prize to C. Rubbia and S. Van der Meer, who made $p\overline{p}$- collider a reality with the invention of a new accelerator technique (‘Stochastic cooling’)

View of the UA1 Experiment



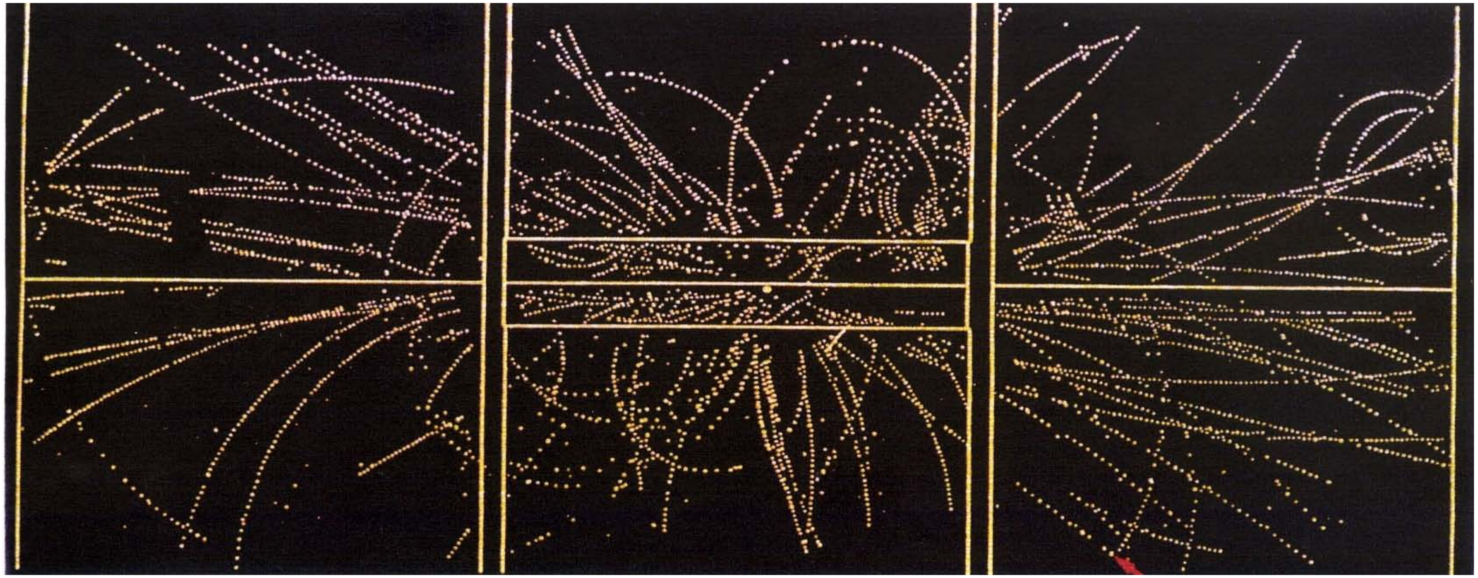
The CERN Super proton synchrotron
Was converted into a collider
(see discussion on accelerators)

UA1 was at the time the most complex
Particle physics experiment

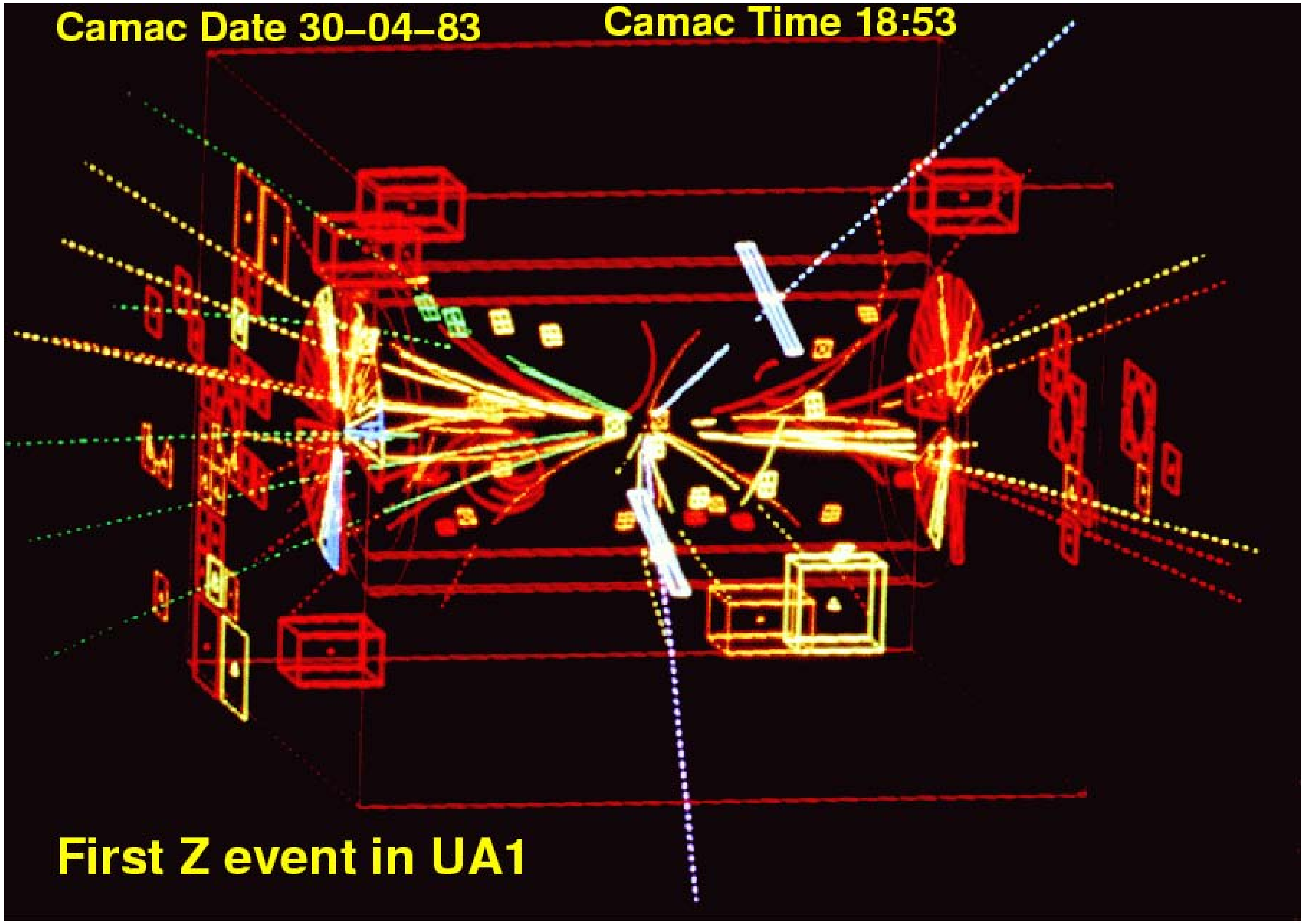
The white-orange-white cylinder was a gas-filled detector to record the ionisation of charged tracks

The Vienna Institute of High Energy Physics (HEPHY) was a collaborator in this experiment

Computer reconstruction of tracks in the UA1 Central Tracking Detector (2-D view)



The first Z event in UA1

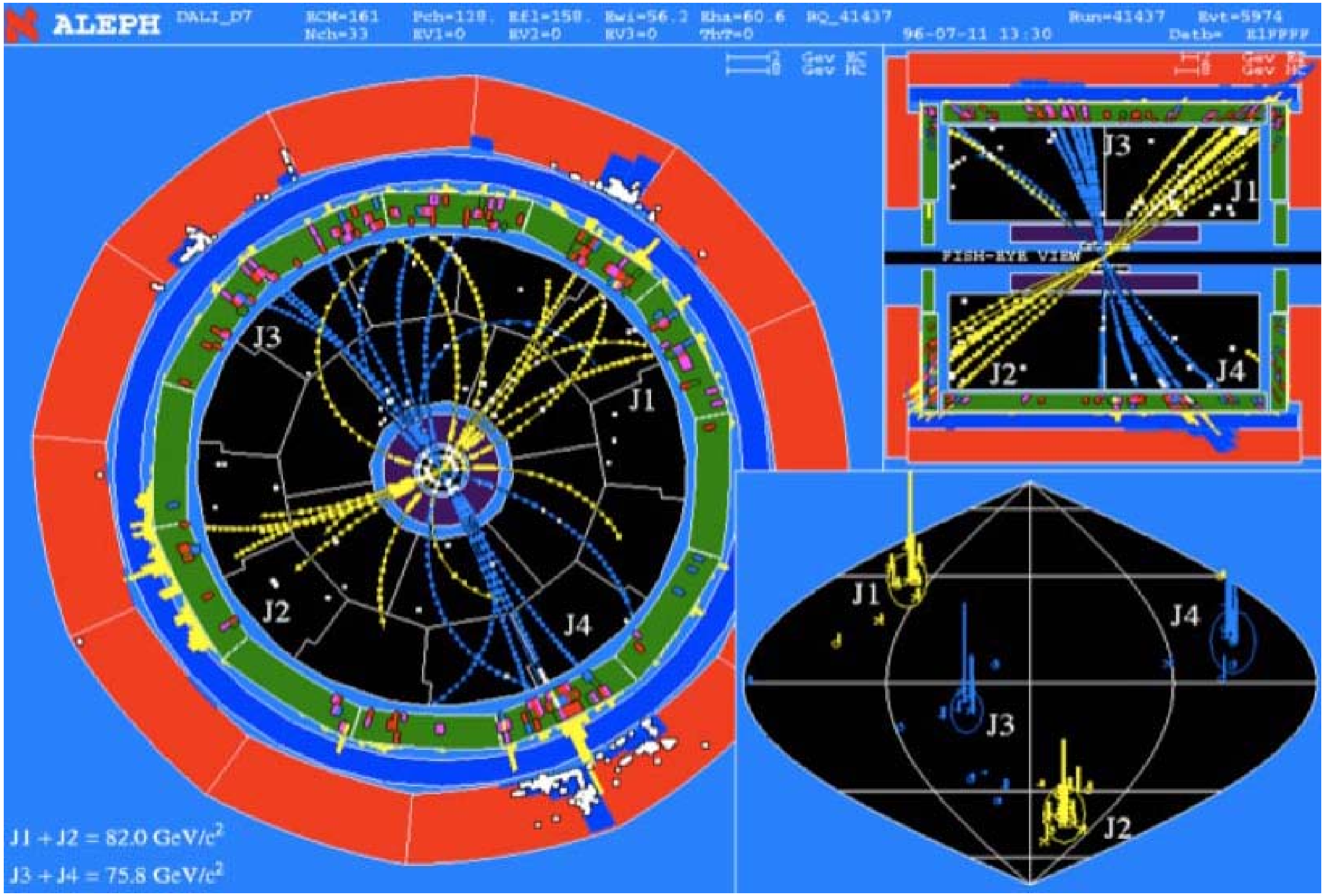


$Z \to e^+ \ e^-$

1978 - ?: The Inexorable Rise of the Standard Model (SM)

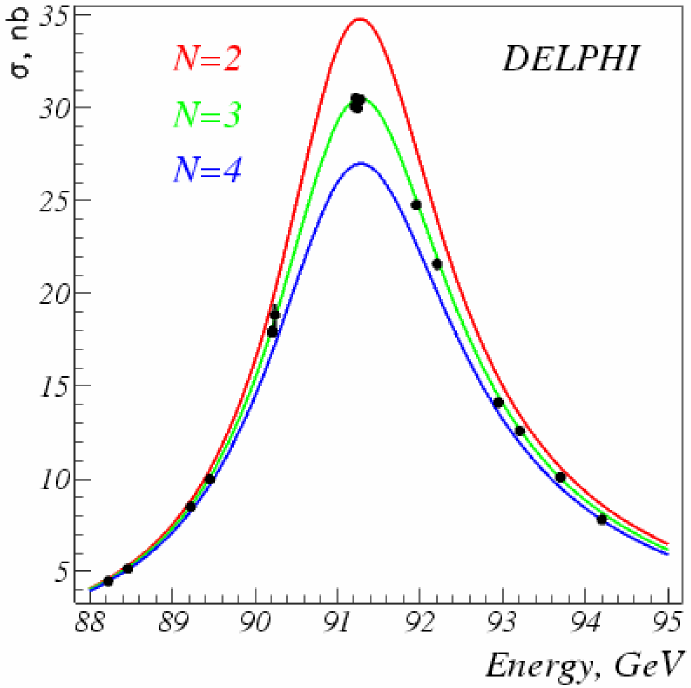
- Today's physics world is made of
  - four interactions: *gravitation, weak, electromagnetic, strong*
  - 12x3 quarks and 12 leptons
  - 4 IVB's for ew force
  - 8 gluons, mediating the strong force
  - Higgs particle (explained later)
- There are 61 particles …
  - is this really one fundamental description ?
- The obvious question: why 3 generations of quarks
  - perhaps: matter-antimatter symmetry ?
- After the $p\bar{p}$ collider, the 'Discovery Machine' the LEP e^+e^- collider was the next logical step to ALLOW precise tests of the Standard Model

LEP: Large Electron Positron collider



Computer reconstruction
Of particles in on LEP
Experiment (ALEPH)

A classic LEP Result

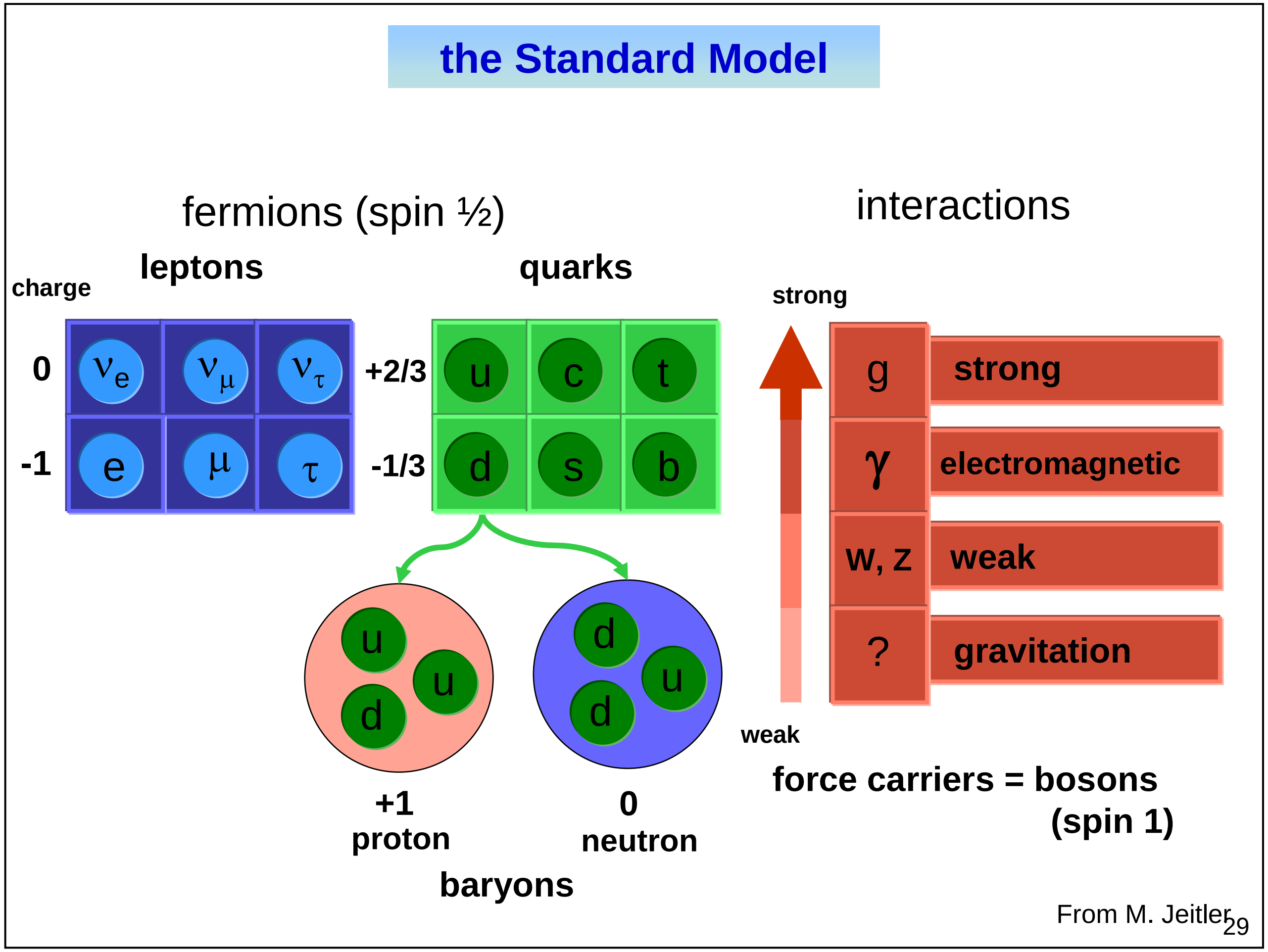


$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

3 Neutrino Familien mit $m_\nu \leq \frac{m_Z}{2}$

3 Quark Families

Elementary Particles in the Standard Model



the Standard Model

fermions (spin ½)

leptons

charge			
0	ν_e	ν_μ	ν_τ
-1	e	μ	τ

quarks

+2/3	u	c	t
-1/3	d	s	b

+1
proton
u u d

0
neutron
d u d

baryons

interactions

strong

g	**strong**
γ	**electromagnetic**
w, z	**weak**
?	**gravitation**

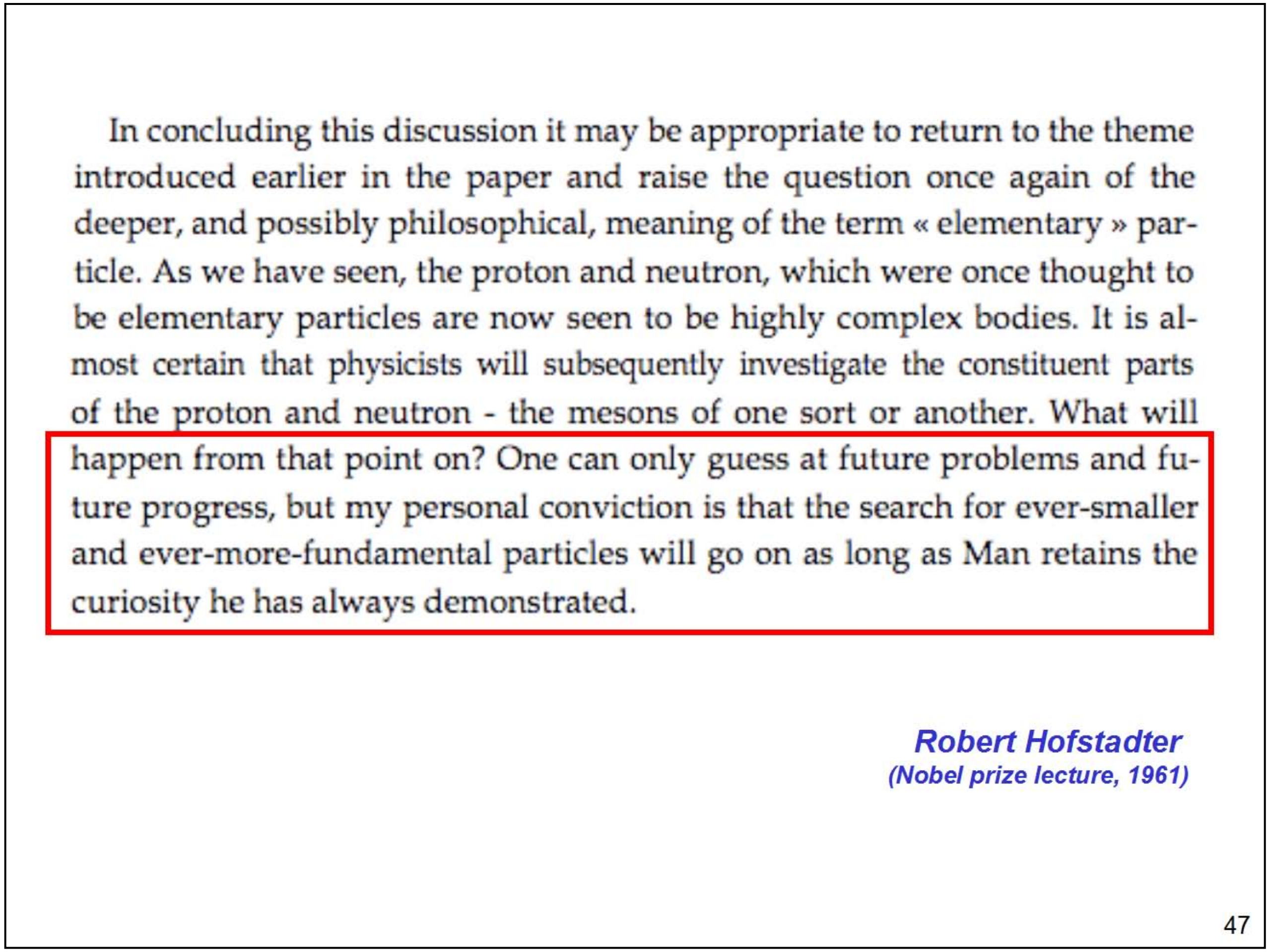
weak

force carriers = bosons
(spin 1)

From M. Jeitler

- the Standard Model describes all known particles
- **leptons** are elementary particles that can be observed as such
- **quarks** are elementary particles that are observed only in combinations of three quarks (“**hadrons**”) or of a quark and an anti-quark (“**mesons**”); differently from leptons, they bear the so-called “**color charge**”
- both leptons and quarks are “**fermions**”, i.e. particles with half-integer spin which obey the “**Fermi-Dirac statistics**”: no two identical particles can occupy the same quantum state (“**Pauli exclusion principle**”)
- both leptons and quarks exist in 3 “generations”; only the first-generation particles are stable (except for neutrinos)
- interactions (4 types) are mediated by particles: “**gauge bosons**” (bosons are particles with integer spin and obey the “Bose-Einstein statistics”: identical particles tend to flock together in the same location and quantum state)

Hofstadter: what is elementary ?



In concluding this discussion it may be appropriate to return to the theme introduced earlier in the paper and raise the question once again of the deeper, and possibly philosophical, meaning of the term « elementary » particle. As we have seen, the proton and neutron, which were once thought to be elementary particles are now seen to be highly complex bodies. It is almost certain that physicists will subsequently investigate the constituent parts of the proton and neutron - the mesons of one sort or another. What will happen from that point on? One can only guess at future problems and future progress, but my personal conviction is that the search for ever-smaller and ever-more-fundamental particles will go on as long as Man retains the curiosity he has always demonstrated.

Robert Hofstadter
(Nobel prize lecture, 1961)