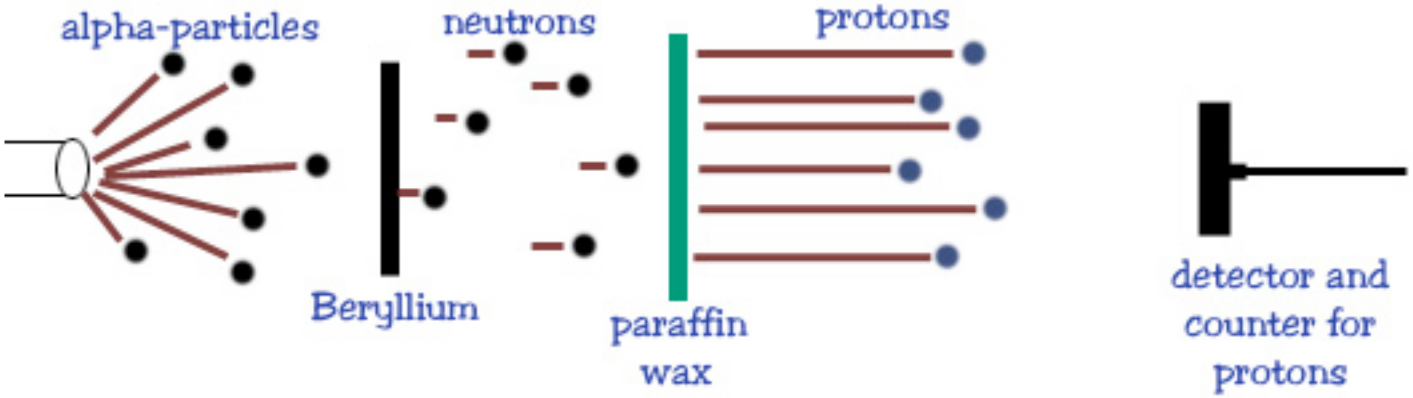
The Chadwick's experiment



$$U_p = \frac{2M}{M+1} V$$

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

$$U_n = \frac{2M}{M+14} V$$

U_p = ca. 3.7×10^{9} cm/sec, U_n = ca. 4.7×10^{8} cm/sec.

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Anderson Discovers the muon (1)

1937 - S. H. Neddermeyer and C. D. Anderson, measurements of energy loss of cosmic-ray particles. They used cloud chamber with 1-cm platinum plate inside. By measuring the curvature of the tracks on both sides of the plate, they were able to determine the loss in momentum.
p=100-500 MeV/c from track curvatures;
$E=pc$ assuming particles were electrons or positrons (relativistic).

- Two types of particles: "shower" particles and "penetrating" particles.
- **Bethe-Heitler** theory predicted large energy loss for electrons and smaller losses for heavier particles. **Neddermeyer and Anderson** concluded that penetrating particles are heavier than electron.
- They could not be protons because protons would be slower and would ionise medium stronger.

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Anderson Discovers the muon (2)

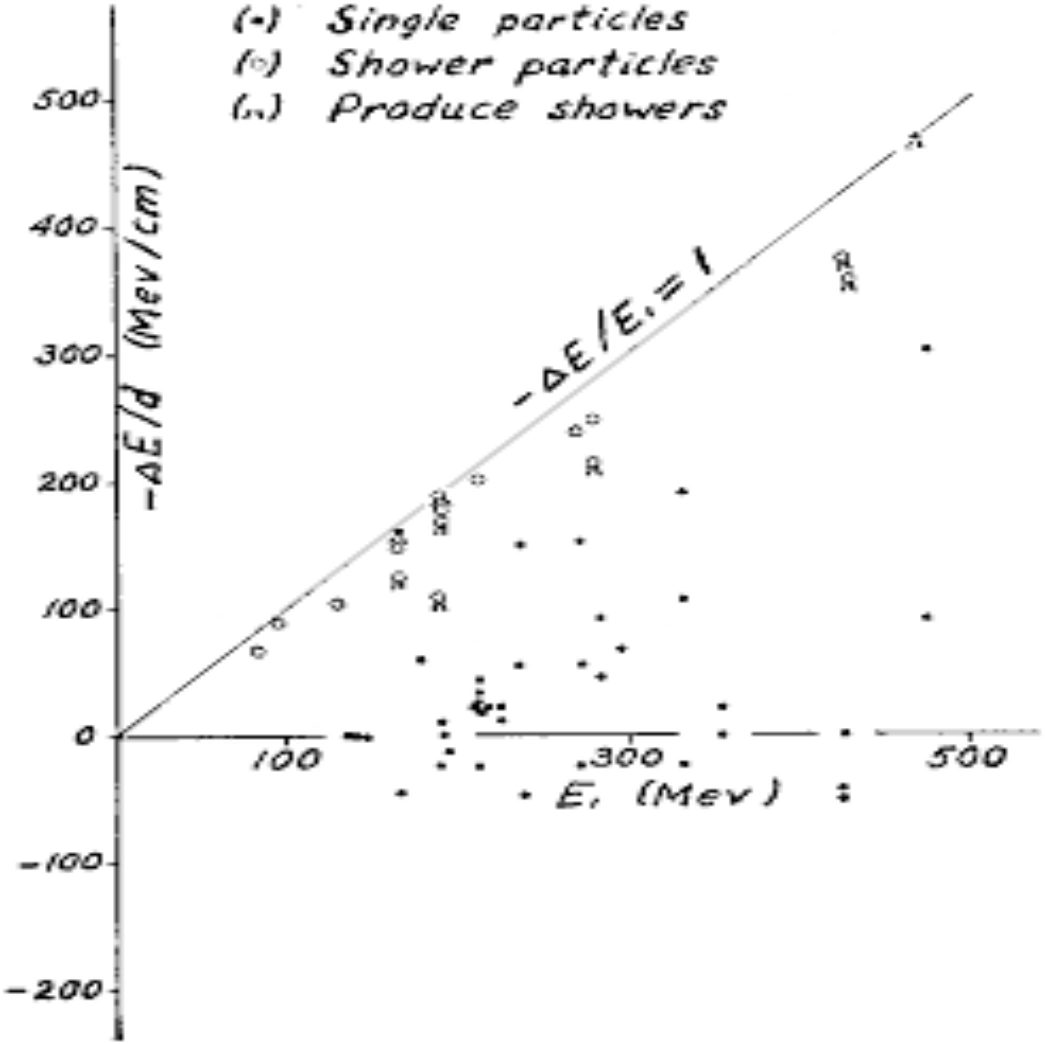
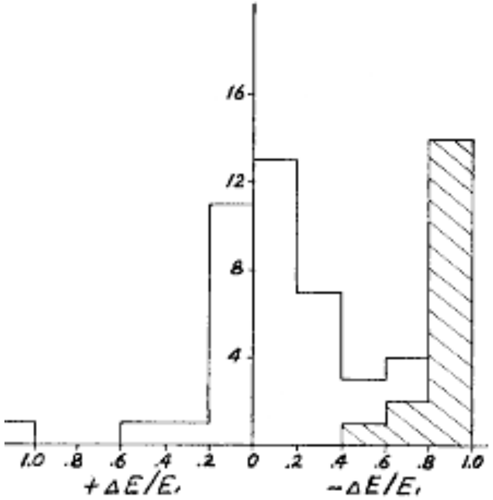


FIG. 1. Energy loss in 1 cm of platinum.



istribution of fractional losses in 1 cm of platinum.

$X_0=6.54/21.45=0.3$ cm

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Street Measures the Muon Mass (1)

1937 - **J. C. Street and E. C. Stevenson** - determination of the mass of the new particle.

- Simultaneous measurement of particle momentum and ionisation: $p=mv\gamma$, $dE/dx \propto 1/v^2$.
- The ionisation depends weakly on the velocity except when the velocity is low, that is when the particle is near the end of its path.
- Cloud chamber was triggered by 3-fold coincidence and anticoincidence (method invented by **Blackett and Occhialini**)

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Street Measures the Muon Mass (2)

Scheme of the experiment:
1, 2, 3 - counters in coincidence;
L - lead filter to remove shower particles;
C - cloud chamber with 3500 gauss magnetic field;
4 - group of counters in anticoincidence.
Only particles which stop in the cloud chambers were photographed.

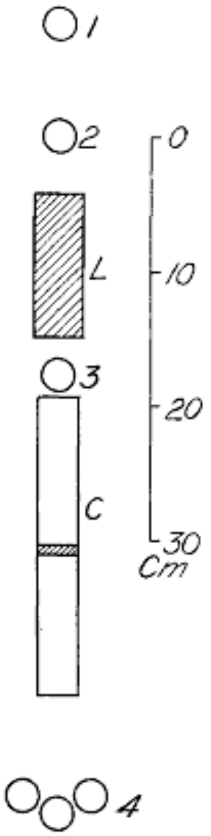

Fig. 1. Geometrical arrangement of apparatus.

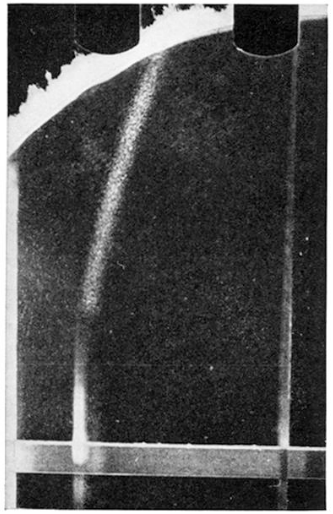

Fig. 3. Track *B*.

Typical event with penetrating particle. Momentum is determined from the track curvature. Ionisation density is 6 times as great as normal thin tracks (electrons). If the ionisation density varies inversely as velocity squared, the rest mass is approximately 130 times the rest mass of the electron.

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Yukawa (1)

1935 - H. Yukawa predicted the existence of a particle of mass intermediate between the electron and the proton.

- This particle was to carry the nuclear force in the same way as the photon carries the electromagnetic force.
- In addition it was to be responsible for beta-decay.
- The predicted mass of the particle was about 200 MeV/c^2.
- The mass of the new penetrating particle, seen by **Neddermeyer and Anderson** and by **Street and Stevenson** was determined (after improved measurements) to be about 100 MeV/c^2, close enough to the theoretical estimate to make natural the identification of the penetrating particle with the **Yukawa** particle.

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Yukawa(2)

- **Tomonaga and Araki** showed in 1940 that positive and negative **Yukawa** particles should produce different effects when they stopped in matter.
- Positive particle should decay.
- Negative particle should be captured into atomic-like orbits, but with very small radii. As a results, the orbits should overlap the nucleus. The particle should interact with the nucleus and be absorbed before it could decay.
- The life time of the penetrating particle was measured as 2.2×10^{-6} s.
- **Conversi, Pancini and Piccioni** during the World War II investigated the decays of positive and negative penetrating particles in different materials.
- They found that positive particles always decayed when stopped in matter, while negative particles were absorbed by the nuclei in iron but decayed in carbon, in contradiction to the **Tomonaga-Araki** predictions.

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Pancini Piccioni Conversi

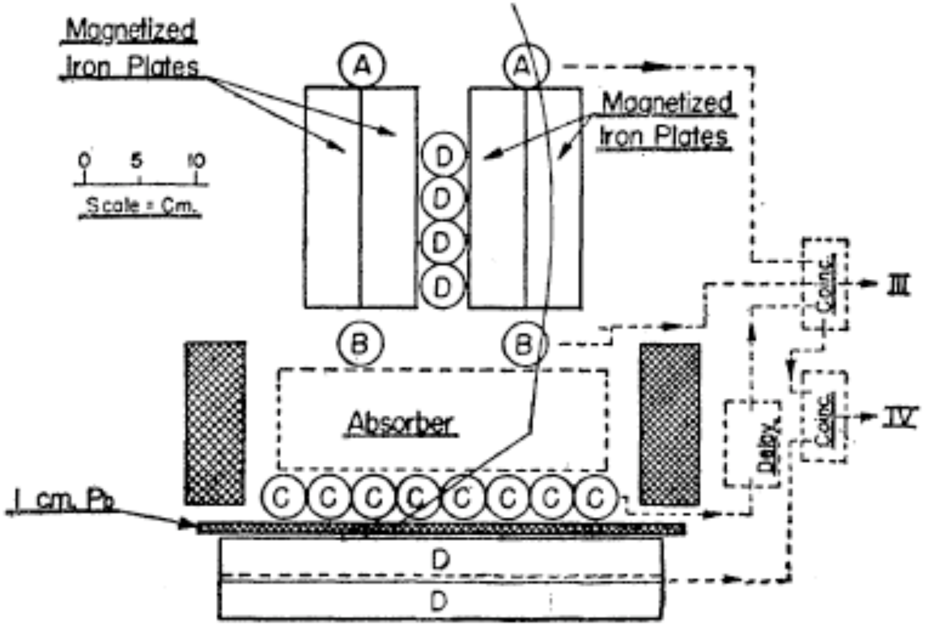

FIG. 1. Disposition of counters, absorber, and magnetized iron plates.
All cour

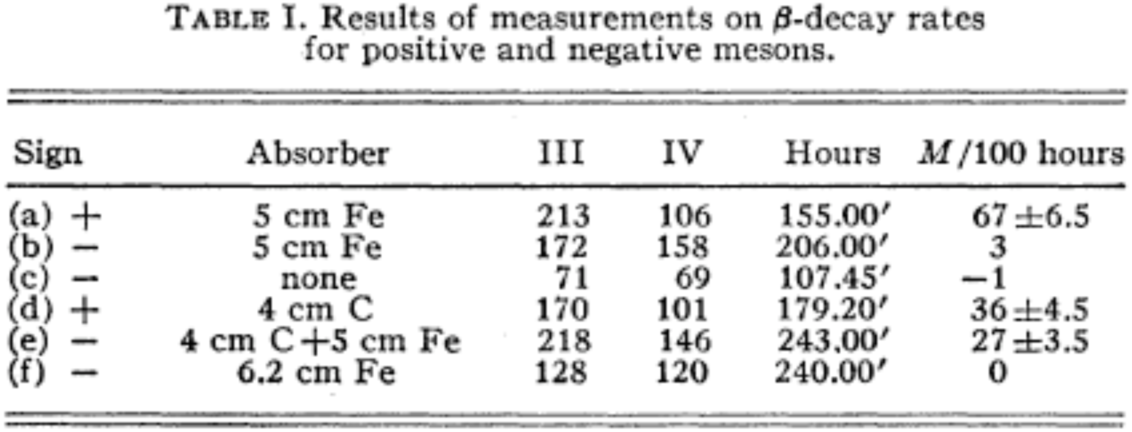

TABLE I. Results of measurements on β-decay rates for positive and negative mesons.

Sign	Absorber	III	IV	Hours	M/100 hours
(a) +	5 cm Fe	213	106	155.00′	67±6.5
(b) −	5 cm Fe	172	158	206.00′	3
(c) −	none	71	69	107.45′	−1
(d) +	4 cm C	170	101	179.20′	36±4.5
(e) −	4 cm C+5 cm Fe	218	146	243.00′	27±3.5
(f) −	6.2 cm Fe	128	120	240.00′	0

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The pions of Powell

The meson

- What holds the nucleus together ?
  - protons are positive !
- Strong force of short range ; Yukawa calculated the mass of the exchanged particle from the range ~ 300 times the mass of the electron
- 1937 : Anderson + Stevenson measure the mass of the most copious particle in the cosmic rays to be in that range
- 1947 Pancini Piccioni Conversi show that this particle has very small interaction with nuclei. Phys Rev 71 (209) 1947
- 1947 Powell shows that there are two middle weight particles in the cosmic rays Nature 159, (694) 1947

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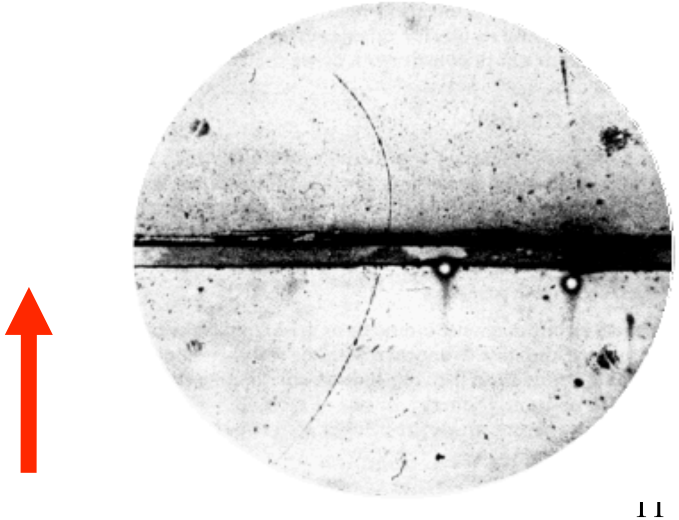
Antiparticles

- Dirac equation has two solutions , one with negative energy
- After positron discovery, Feynman proposes that the negative energy solution can be re-expressed as a positive energy state of the anti-particle

Crossing symmetry

$$\begin{aligned} A &\rightarrow \bar{B} + C + D \\ A + \bar{C} &\rightarrow \bar{B} + D \\ \bar{C} + \bar{D} &\rightarrow \bar{A} + \bar{B} \end{aligned}$$



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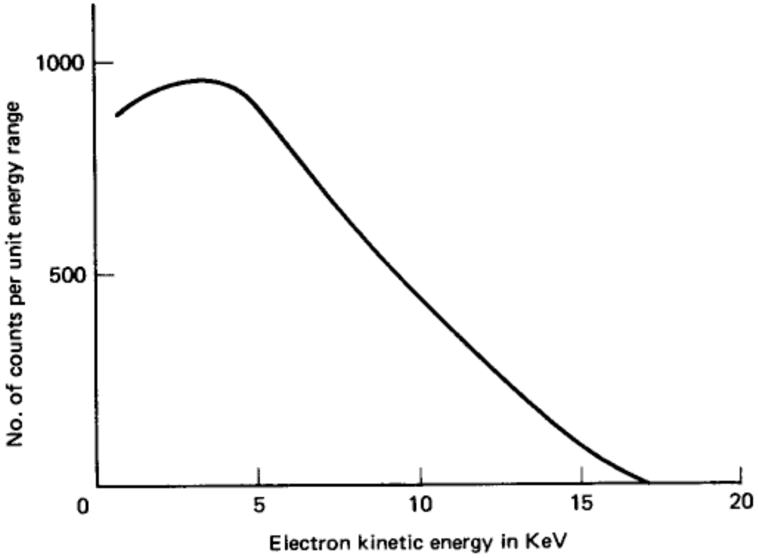
Neutrinos

- Beta decay of Nuclei featured a momentum spectrum that was not a spike !
- Pauli proposed the “neutron” and Fermi eventually called it neutrino
- $\pi \dashrightarrow \mu\ \nu$
- $\mu \dashrightarrow e\ 2\ \nu$



- Cowan and Raines make the first observation of the neutrino in
  - $\nu^{bar} + p^+ \dashrightarrow n + e^+$
- Davis and Harmer show that the neutrino and antineutrino are two distinct particles by measuring that the reaction $\nu^{bar} + n \dashrightarrow p^+ + e^-$ does not occurr

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LEPTON NUMBER Conservation

$$\mu^- \not\to e^- + \gamma$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Lederman Schwartz and Steinberger show that the muon neutrino is not the electron neutrino

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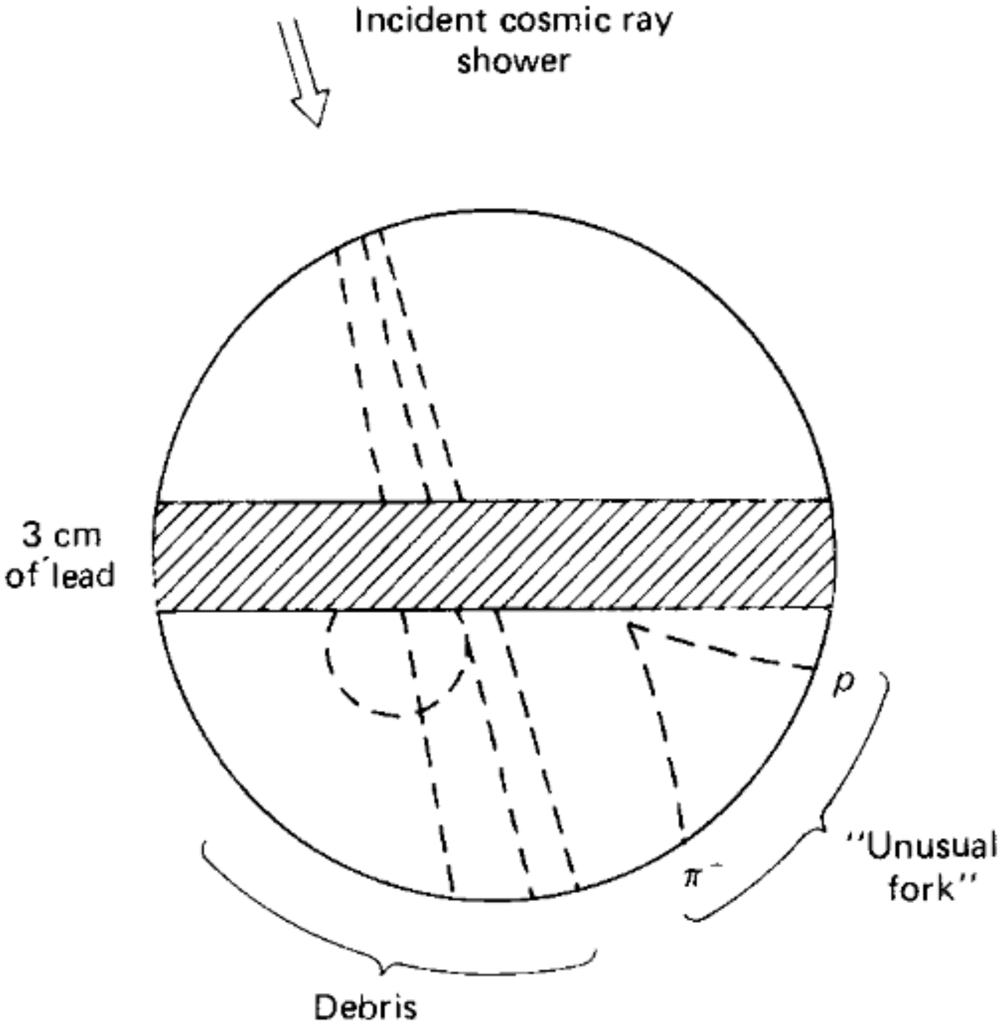
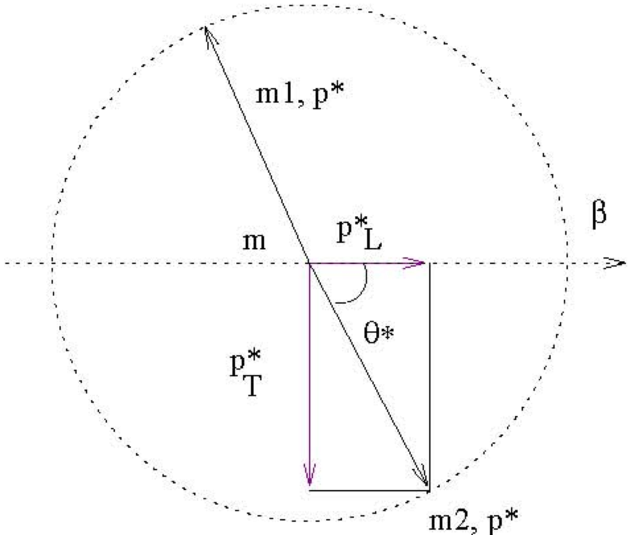
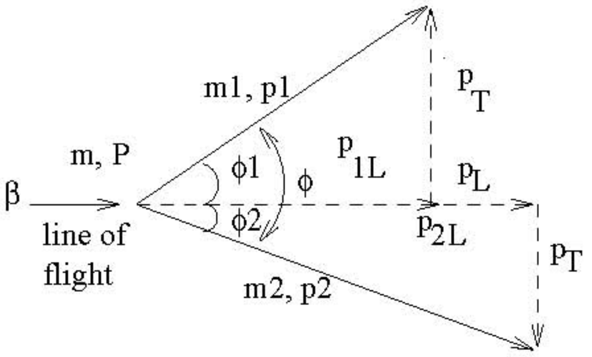
A “strange” event

Rochester and Butler 1947



Armenteros (1)





$$p_T = p^* \sin\vartheta^*$$

$$\alpha = \frac{2p^*\cos\vartheta^* + \beta(E_+^* - E_-^*)}{\beta(E_+^* + E_-^*)}$$

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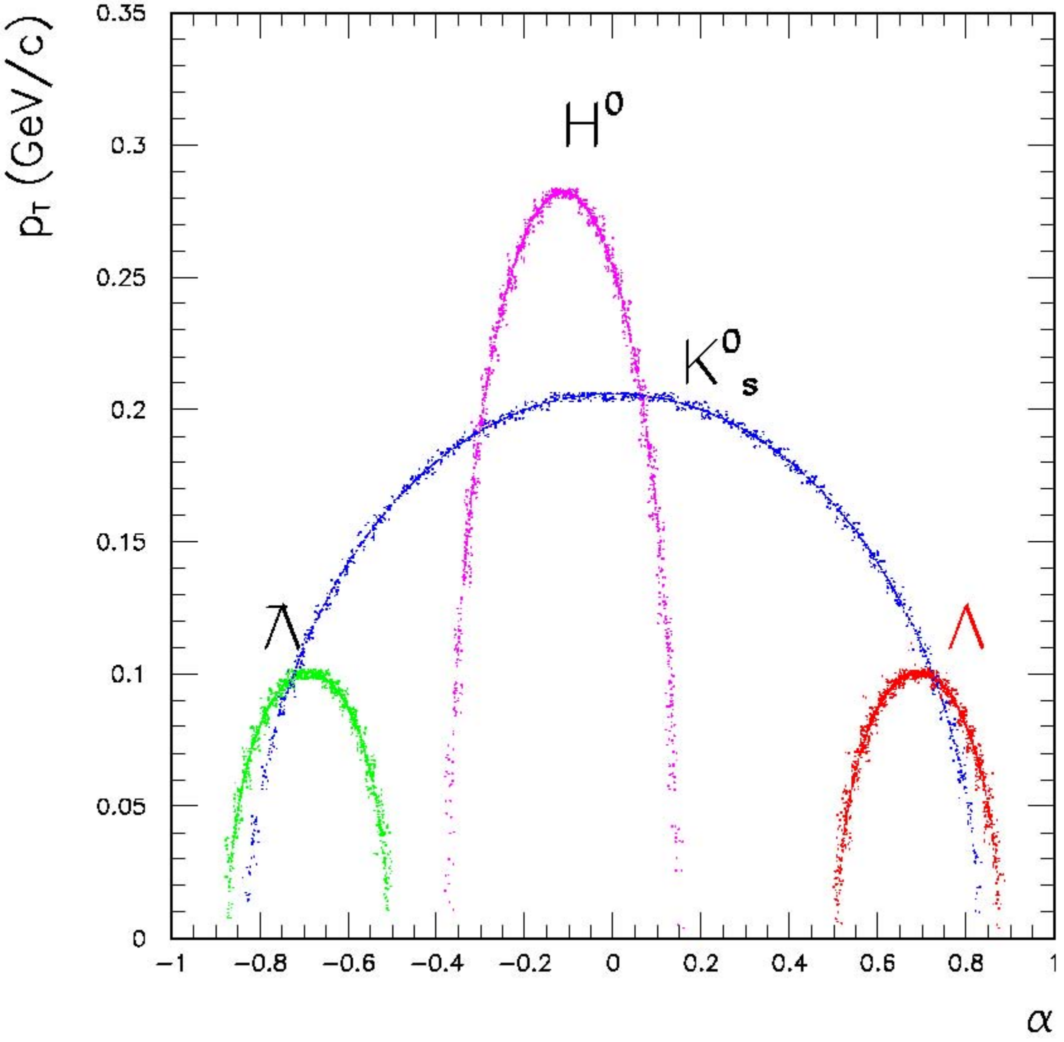
Armenteros (2)

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

$$\Lambda \rightarrow p\pi^-$$

$$\bar{\Lambda} \rightarrow \bar{p}\pi^+$$

$$H \rightarrow \Sigma^- p$$



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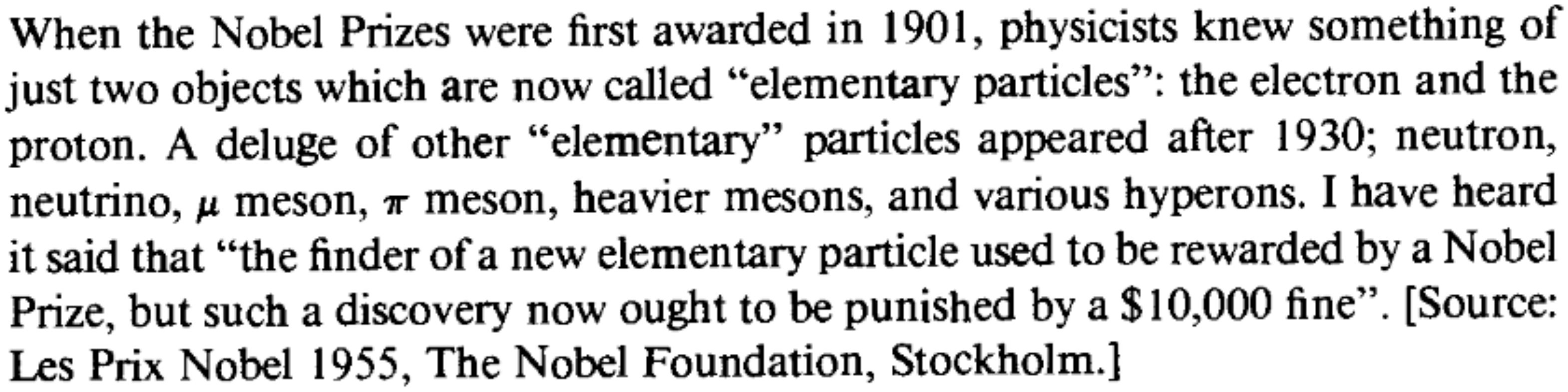
…… and in the following years many particles were discovered

LAMB Nobel speech 1955



When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called "elementary particles": the electron and the proton. A deluge of other "elementary" particles appeared after 1930; neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons. I have heard it said that "the 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". [Source: Les Prix Nobel 1955, The Nobel Foundation, Stockholm.]

Many of these particles where easily produced (copiously) on time scale of 10^{-23} sec but decayed on a much longer time scale 10^{-10} sec !

Strangeness

Strong Interaction

$$\begin{aligned} \pi^- + p^+ &\longrightarrow K^+ + \Sigma^- \\ &\longrightarrow K^0 + \Sigma^0 \\ &\longrightarrow K^0 + \Lambda \end{aligned}$$

Weak Interaction

$$\begin{aligned} \Lambda &\longrightarrow p^+ + \pi^- \\ \Sigma^+ &\longrightarrow p^+ + \pi^0 \\ &\longrightarrow n + \pi^+ \end{aligned}$$

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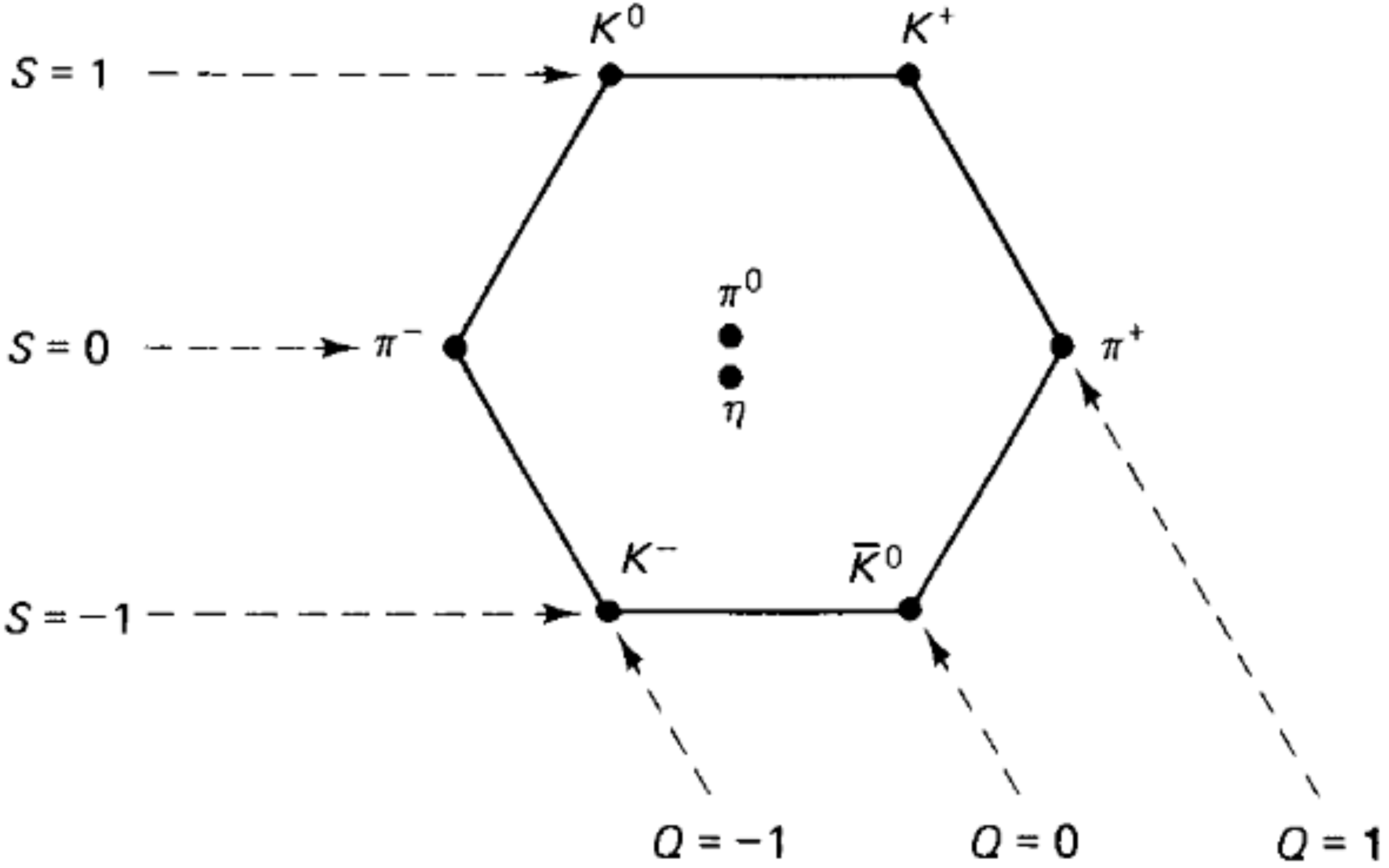
The eight fold way - Mesons



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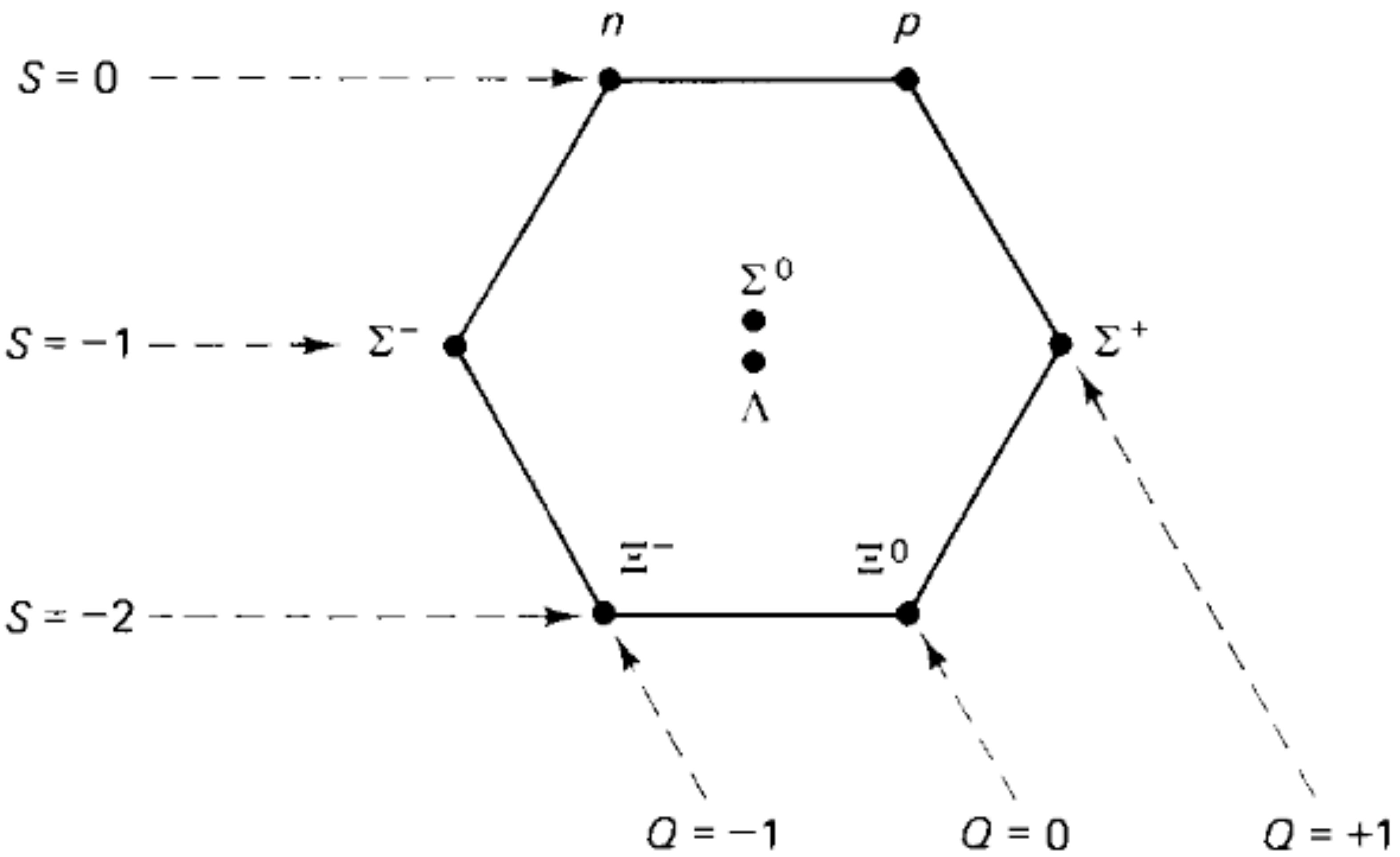
The eightfold way Barions



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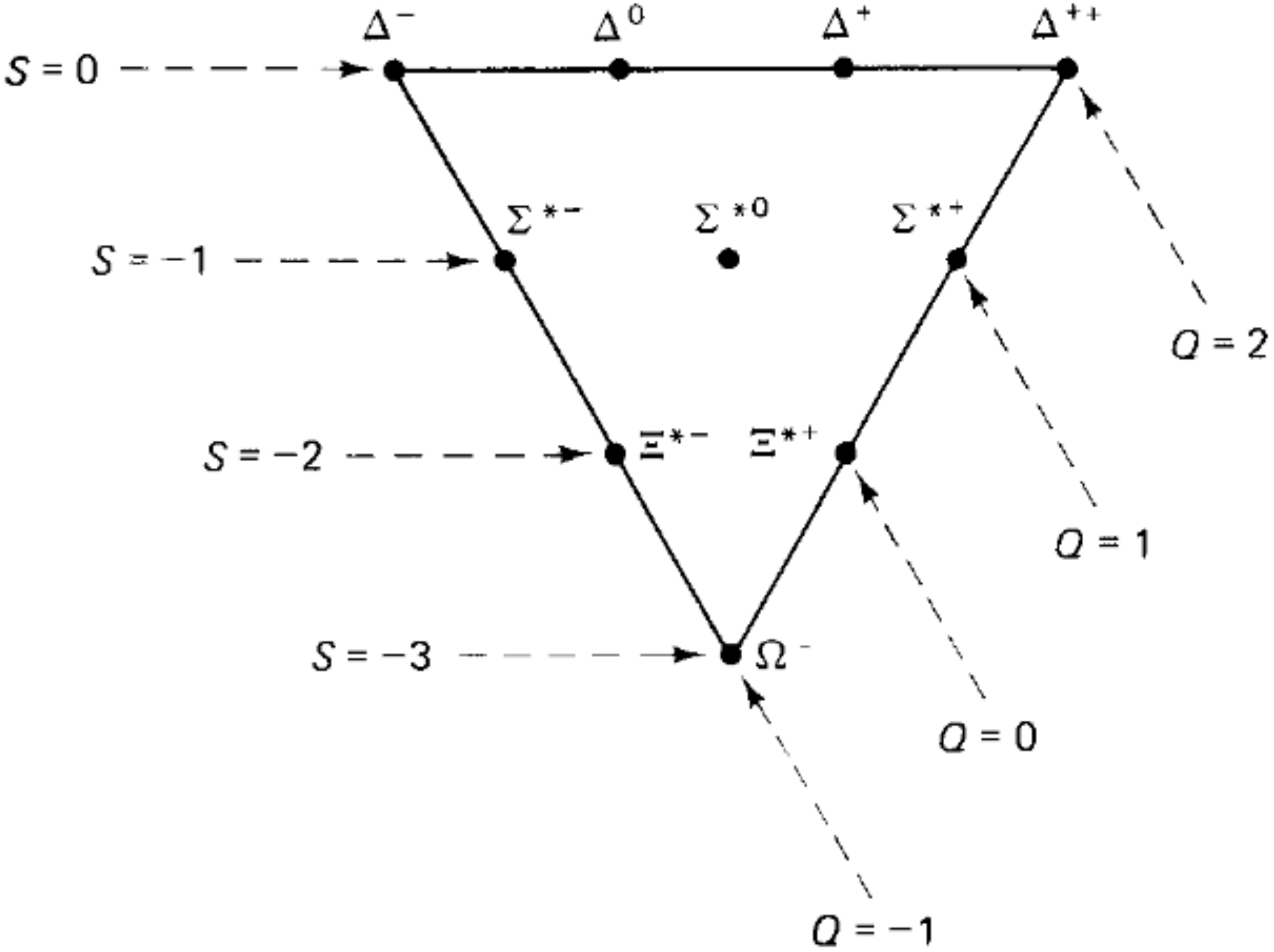
The eightfold way - Barion Decuplet



Exercise: predict Ω^- mass

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Exercise

Members of the Barion decuplet decay into a member of barion octet plus a meson (from the pseudoscalar meson octet). Make the list of possible decays and check the booklet for consistency.

Look at the Δ Σ* Ξ* and Ω (all with spin J=3/2). Compare the picture and the lifetime of the Ω compared with the other members of the decuplet

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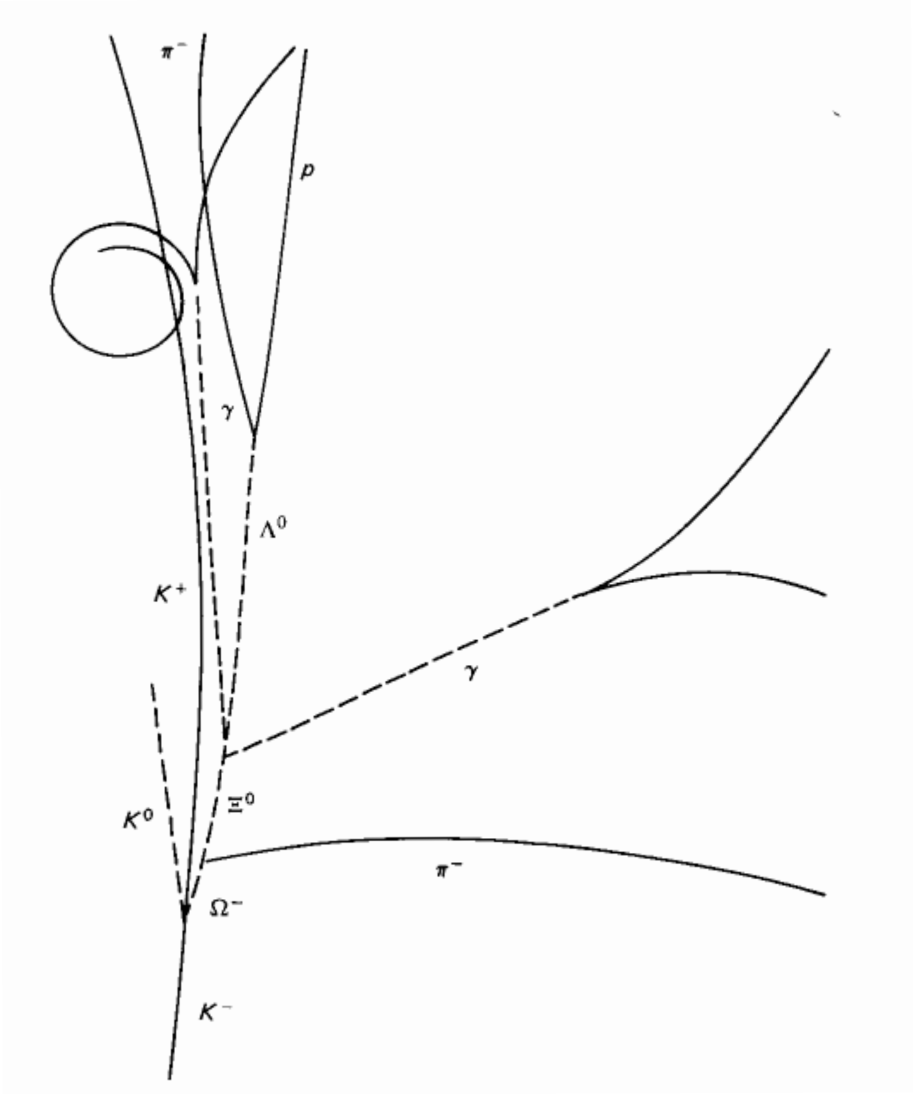
The Ω^-



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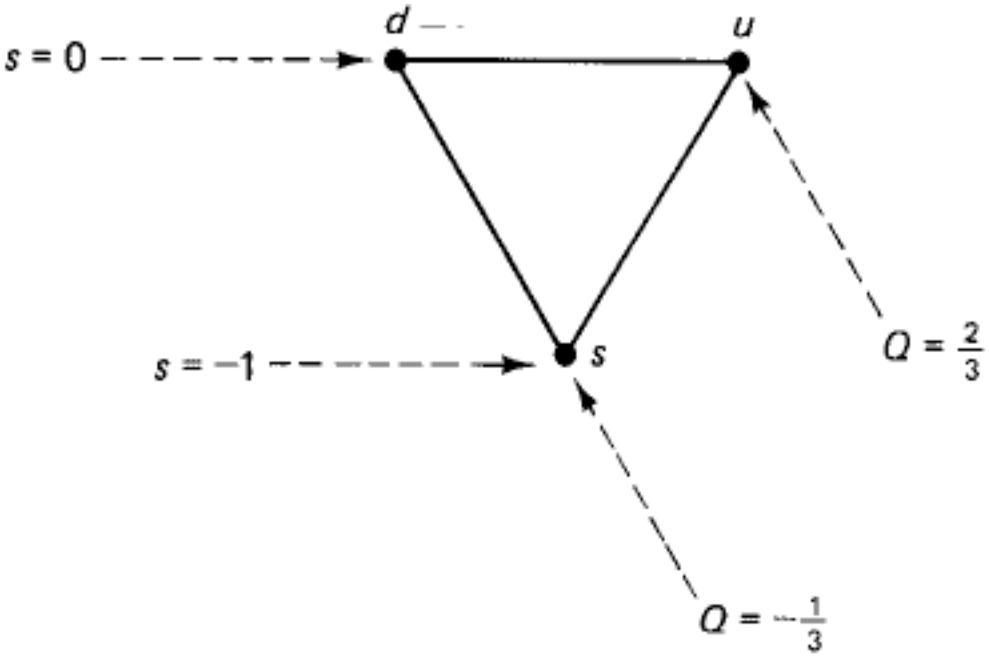
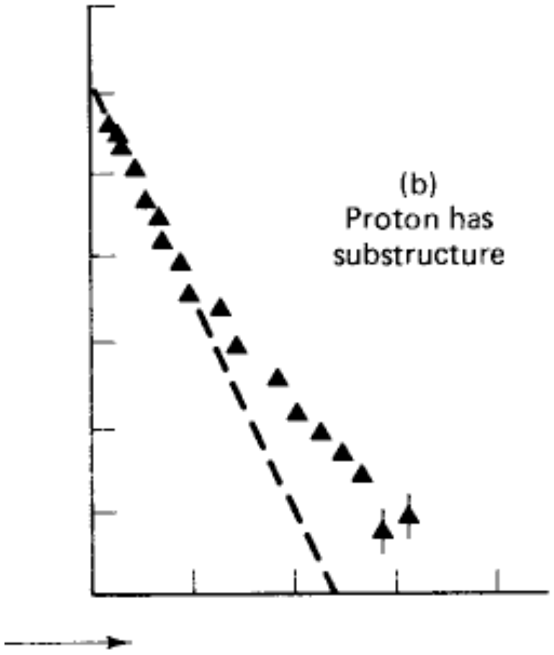
Quark Model





….but no one has ever seen an isolated quark

….. And they also violate Pauli principle

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Exercise

How many barions you can do with 4 quarks . How many have C=3 and c =2

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1974: the year of the revolution

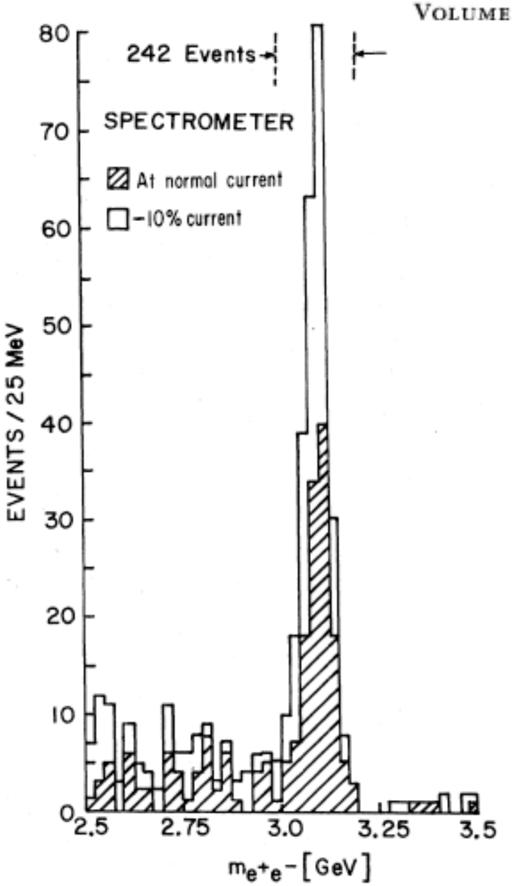
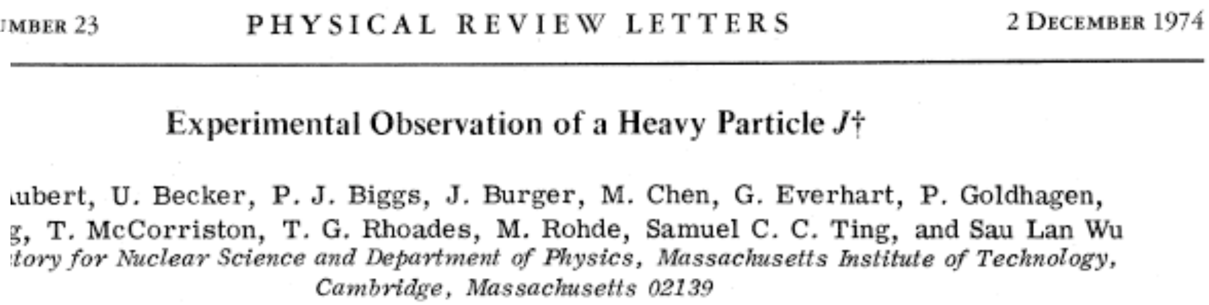


FIG. 2. Mass spectrum showing the existence of *J*. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.


VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle *J*†

ubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen,
g, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
tory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

Leptons: e, ν_e, μ, ν_μ

Quarks: d, u, s c

G.I.M.

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J

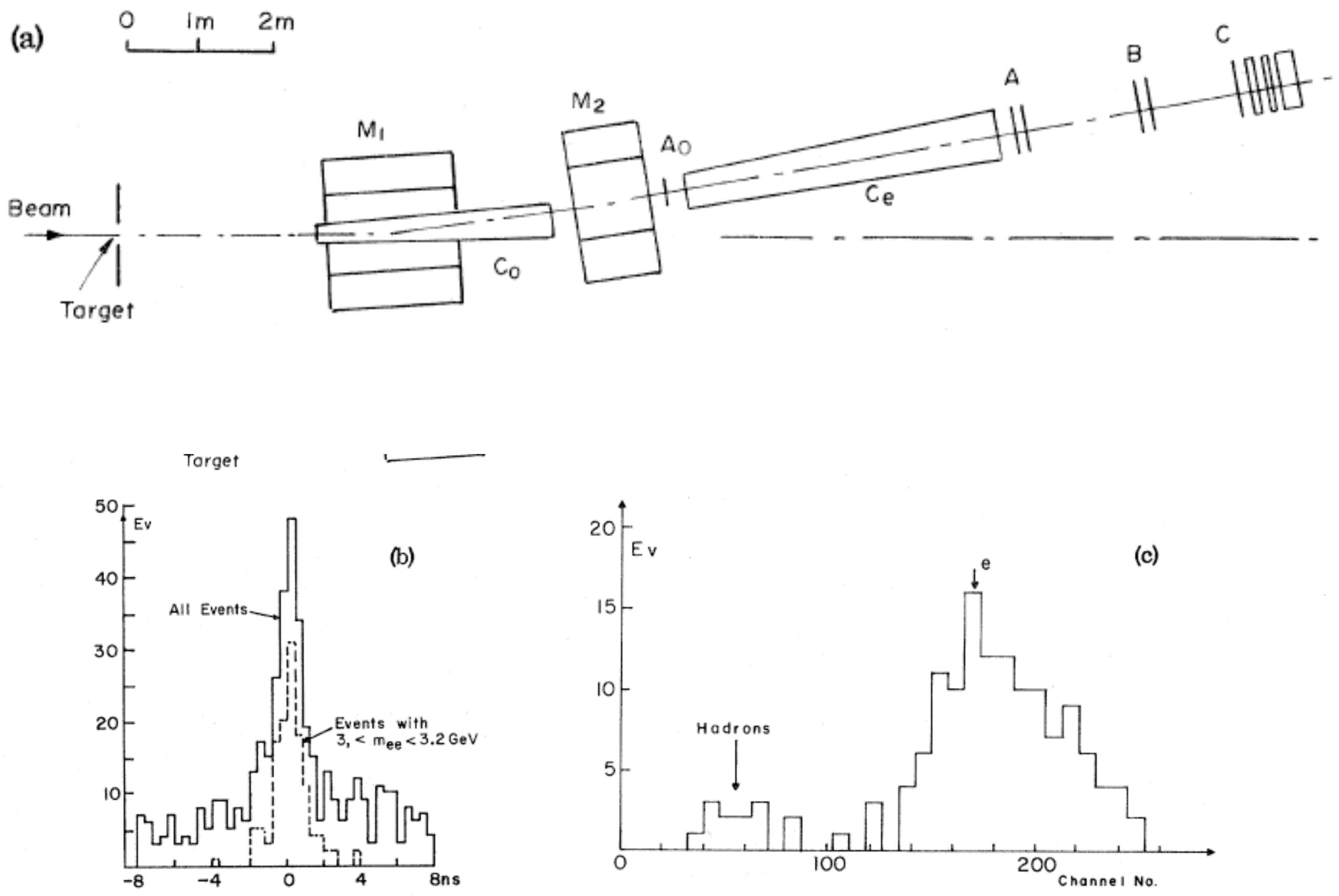
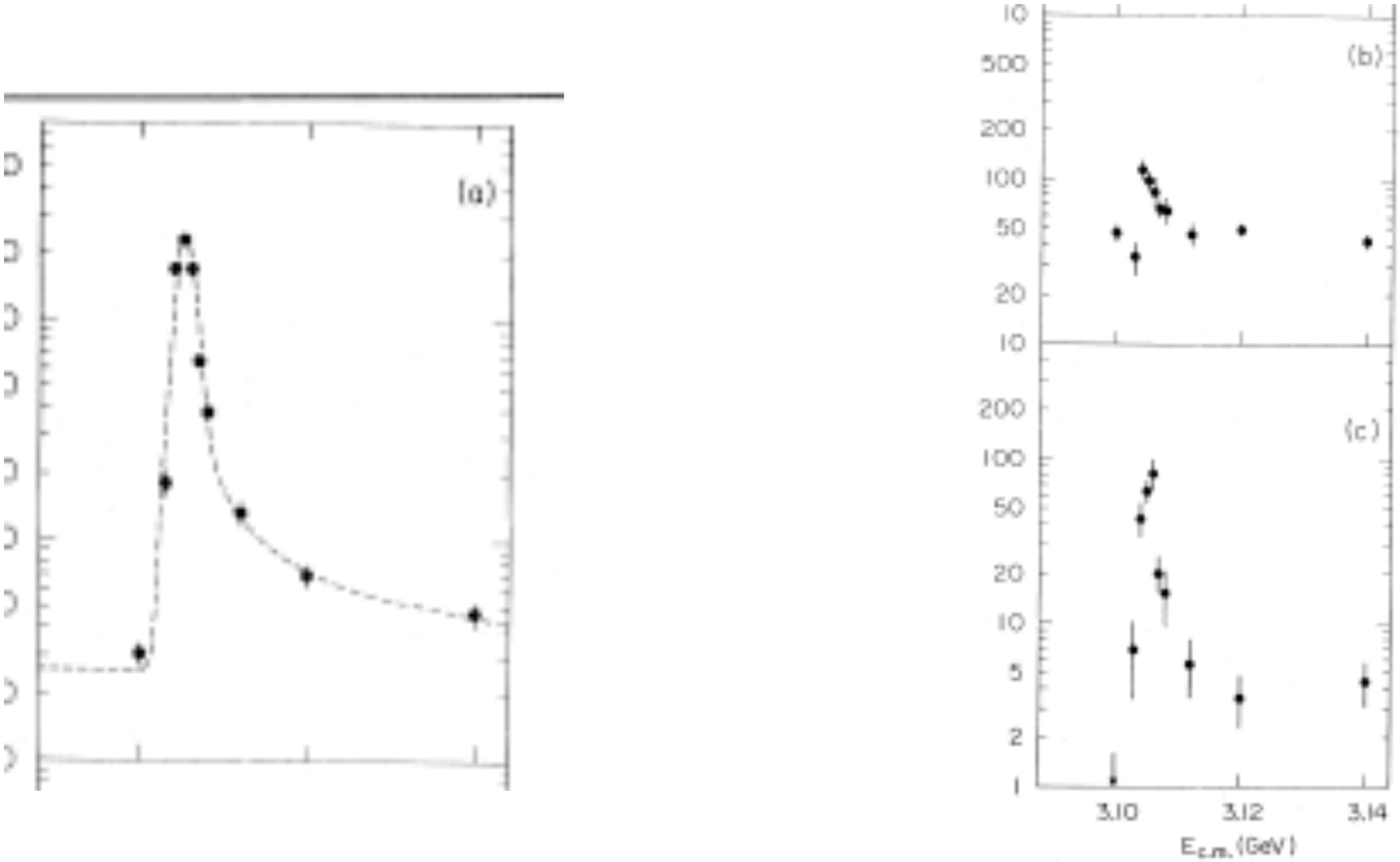


FIG. 1. (a) Simplified side view of one of the spectrometer arms. (b) Time-of-flight spectrum of e^+e^- pairs and of those events with $3.0 < m < 3.2$ GeV. (c) Pulse-height spectrum of e^- (same for e^+) of the e^+e^- pair.

PSI



Cross section versus energy for (a) mu

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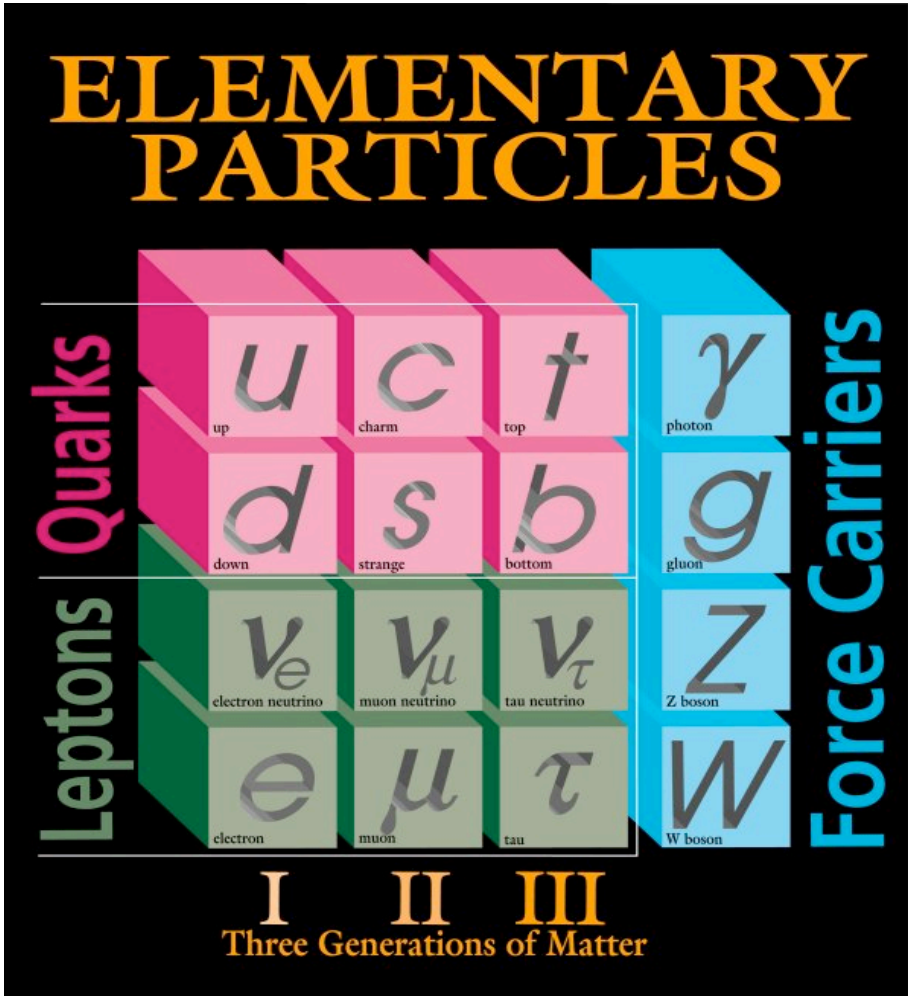
Matters as of today



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