Leptons

Cosmic rays, disc. 1912 Victor Hess

possibly skip this… → [ambient ionizing radiation thought to be due
to radioactivity of earth's crust,
would be expected to decrease as move up.

Hess undertook balloon flights
but found that radiation increased with height]

High energy protons & other nuclei from sun and beyond
strike gas molecules in upper atmosphere,
creating new particles, such as π mesons, K mesons

These then decay into other particles, which
travel to surface of earth.

[see artist's rendition]

1932 Carl Anderson disc. e^+ created by cosmic rays
[see picture of e⁺ e⁻)
A positively charged counterpart to e^- had been
predicted by Dirac in 1930 on basis of his eqn

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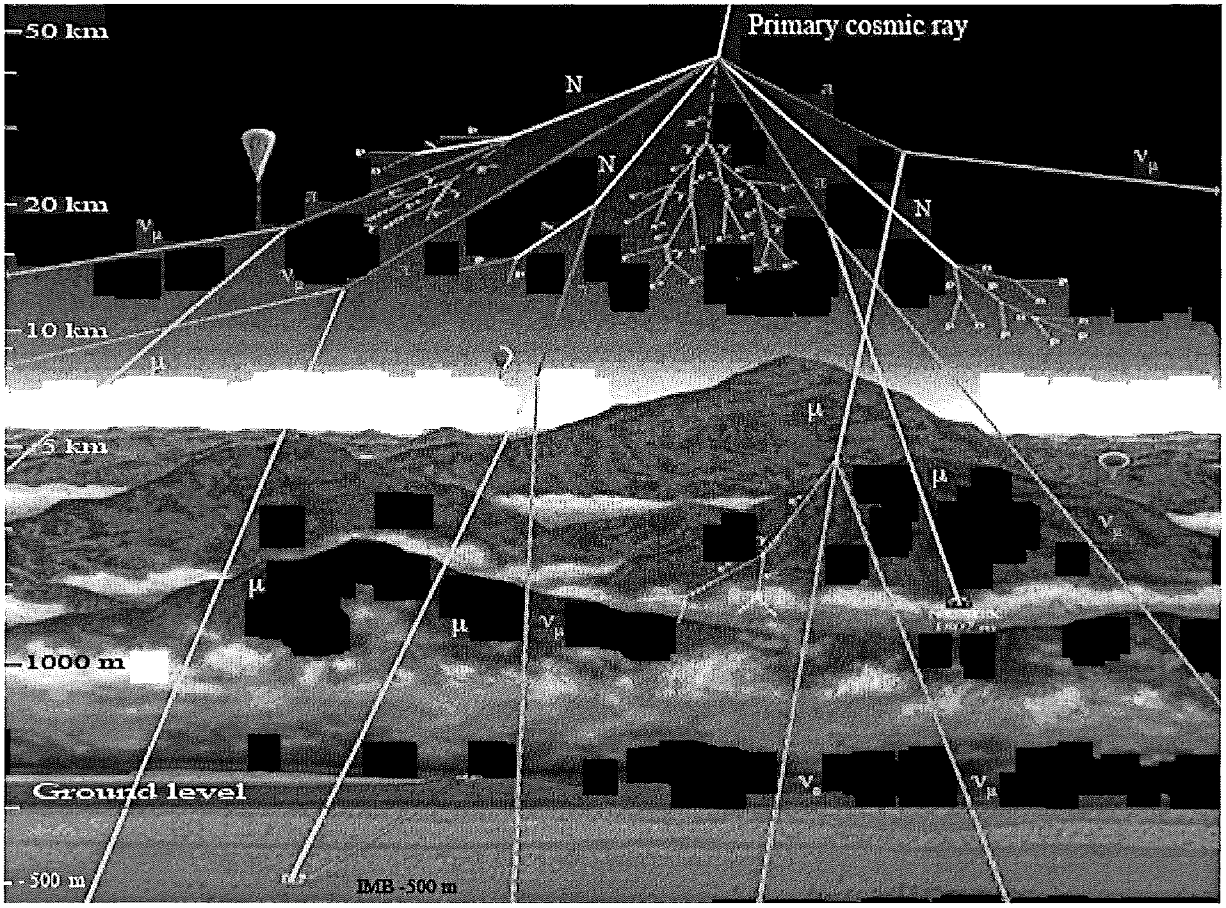
As of 1936,

- e^- (1897)
- e^+ (1930/1932)
- p (1911) $\bar{p}$ (1955)
- n (1932) $\bar{n}$ (1956)
- γ (1905 / 1923)
- ν (pred. 1930 → not disc. until 1956)

all in first gen. [illegible]

Then: μ^- (1937)


50 km
Primary cosmic ray
N
N
N
ν_μ
20 km
ν_μ
ν_μ
10 km
μ
5 km
μ
μ
μ
μ
ν_μ
ν_μ
1000 m
Ground level
ν_e
ν_μ
- 500 m
IMB -500 m

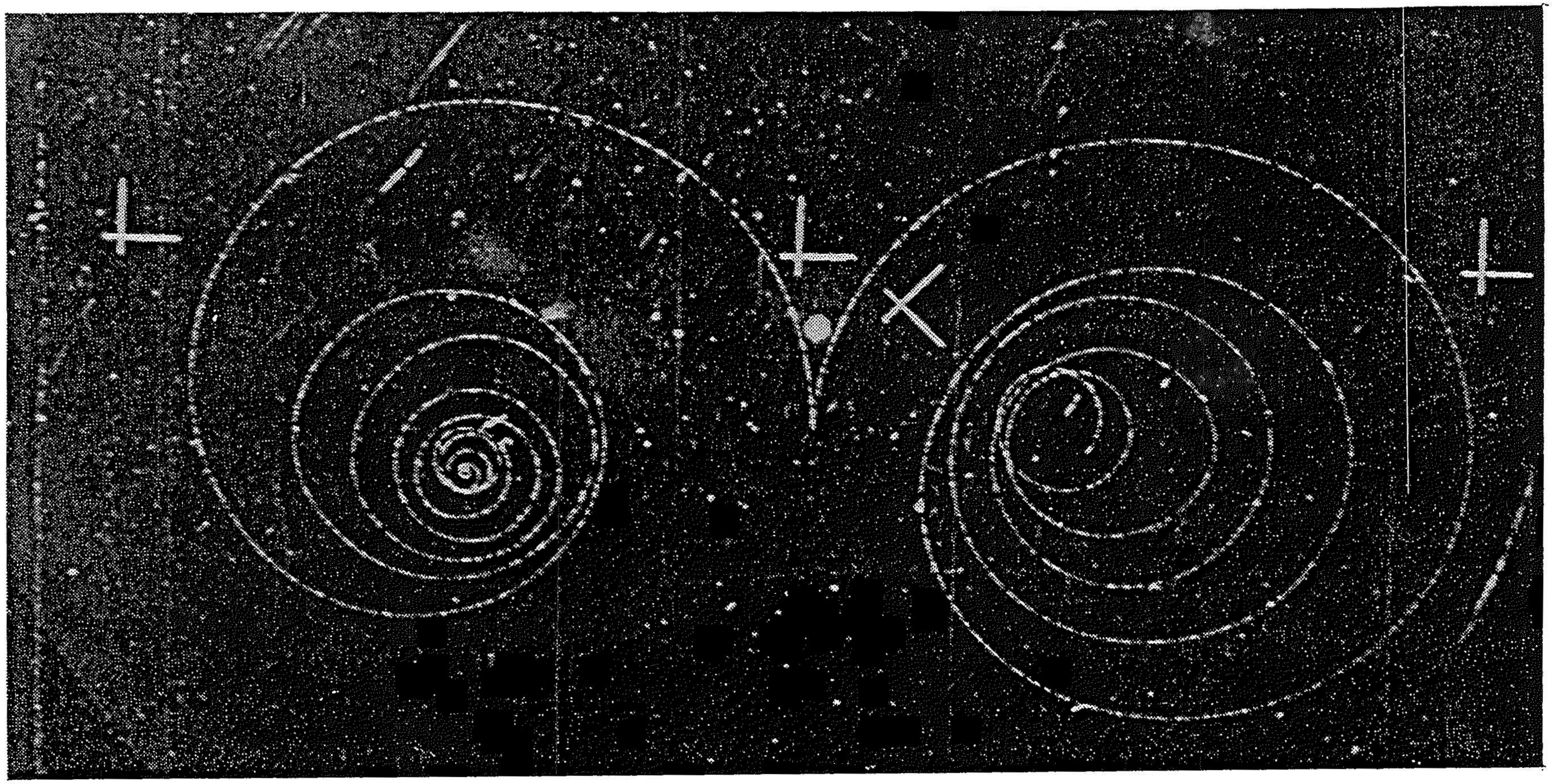


Fig. 6–7 Production of an electron-positron pair in a liquid hydrogen bubble chamber in a magnetic field.

Sources of high energy particles and discovery of new particles

1896 Becquerel discovers radioactivity (α, β, γ)

1897 Thomson discovers e^- in cathode ray tubes

α-particles used as a tool:

- 1911 Rutherford disc. p
- 1932 Chadwick disc n

van de Graff & Cockcroft Walton accelerators

1923 Compton scattering leads to acceptance of photon as particle

1930 Pauli predicts ν (to solve continuous β-spectrum)
not directly detected until 1956

1930 Dirac predicts e^+ (from his eqn)

Cosmic Rays (1912 Victor Hess (balloon flights)
primarily high energy protons (& other nuclei)
from sun (& elsewhere in galaxy)
hit gas molecules → create new unstable particles
(artist's rendition)

1932 Anderson discovers e^+ in cosmic rays

1937 cosmic rays produce $\pi^\pm$, $K^\pm$

$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ [check: lepton # cons.]

$\pi^+ \rightarrow \mu^+ \nu_\mu$

2nd generation leptons [Anderson, Neddermeyer, Street, Stevenson]

μ^- = "heavy electron"

$m_\mu \approx 106$ MeV vs. $m_e \approx 0.511$ MeV

[unexpected; did not explain any unresolved puzzle]

"Who ordered that?" (Rabi)

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unstable

$\tau = 2.2 \times 10^{-6}$ s [longest lived elementary particle]

How far can it travel?

$c\tau = 600$ m

[see photo]

[But many survive to ground level]

moving particle has mean life $\gamma\tau$

$\Rightarrow d = v\gamma\tau$

[HW: if $d = c\tau$, find v]

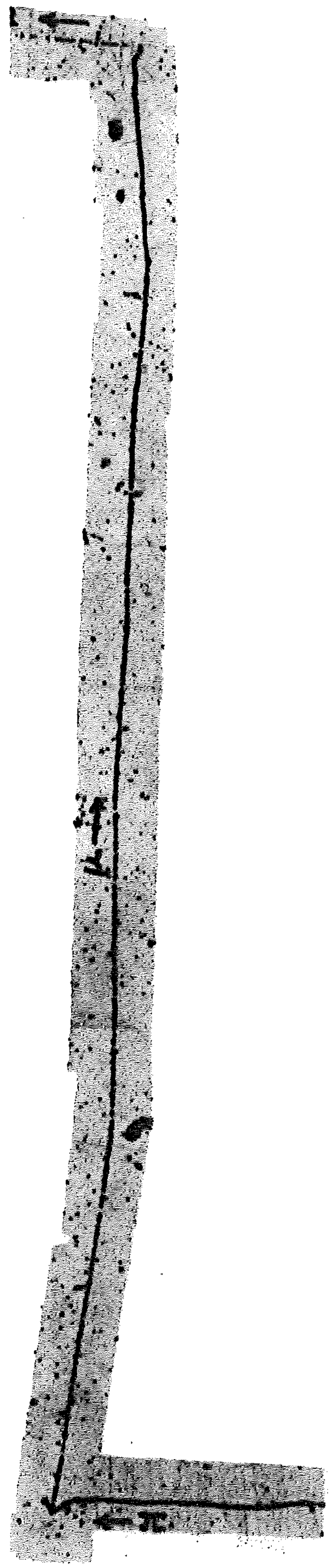


Figure 1.7 Here, a pion decays into a muon (plus a neutrino); the muon subsequently decays into an electron (and two neutrinos). Reprinted by permission from C. F. Powell, P. H. Fowler, and D. H. Perkins, *The Study of Elementary Particles by the Photographic Method* (New York: Pergamon, 1959). First published in *Nature* **163,** 82 (1949).

What does μ decay into?

[photo: 1 charged + neutral]

$\mu^- \to e^- \bar{\nu}$?

No, because electron not monoenergetic [unlike $\pi \to \mu \bar{\nu}$]

[would expect $E_e = \frac{1}{2} m_\mu = 53$ meV]

Also violates lepton # conservation

$\mu^- \to e^- \bar{\nu} \nu$?

[obeys lepton number]

Why not

$\mu^- \to e^- \gamma$? [appears to obey all cons laws]

Not observed

Refine conservation laws:

L_μ = muon #
L_e = electron #
} so $\mu^- \to e^- \gamma$ violates L_μ + L_e

Two neutrino hypothesis: ν_e w/ $L_e = 1$
ν_μ w/ $L_\mu = 1$

$\mu^- \to e^- \bar{\nu}_e \nu_\mu$ obeys all cons laws

1962 experiment at BNL [Schwartz, Steinberger, Lederman]

$\pi^- \to \mu^- \bar{\nu}_\mu$

$\bar{\nu}_\mu p \to n \mu^+$ → also Ice Cube

$\bar{\nu}_\mu p \not\to n e^+$ [not observed]

1- 2005

What would be mean life of μ if $\mu^- \to e^- \gamma$?

$$R = \frac{1}{2m_\mu \hbar} \underbrace{\int (\text{LIPS})_2}_{\frac{1}{2(4\pi)^2} d\Omega} |A|^2 = \frac{|A|^2}{16\pi m_\mu \hbar}$$

A has units of energy. Let A $e \cdot (2m_\mu)$

$|A|^2$ $4e^2 m_\mu^2$ $16\pi\alpha m_\mu^2$

$$R = \frac{\alpha m_\mu}{\hbar}$$

$$\tau = \frac{\hbar}{\alpha m_\mu} \longrightarrow \frac{\hbar}{\alpha (m_\mu c^2)} = \frac{6.6E\text{-}22 \text{ MeV}\cdot\text{s}}{\left(\frac{105}{137} \text{ MeV}\right)} = \boxed{10^{-21} \text{ sec}}$$

1975 discovery of τ^- in accelerators [Perl]

first 3rd generation particle discovered

$m_\tau = 1777$ MeV (even heavier electron)

$$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau \quad [17\%]$$

$$\to e^- \bar{\nu}_e \nu_\tau \quad [18\%]$$

Conservation of lepton numbers L_e, L_μ, L_τ

	L_e	L_μ	L_τ
e^-	1	0	0
e^+	-1	0	0
ν_e	1	0	0
$\bar{\nu}_e$	-1	0	0
μ^-	0	1	0

etc.

	μ^-	$\to$	e^-	$\bar{\nu}_e$	ν_μ	
L_e	0	=	1	− 1	+ 0	✓
L_μ	1	=	0	+ 0	+ 1	✓

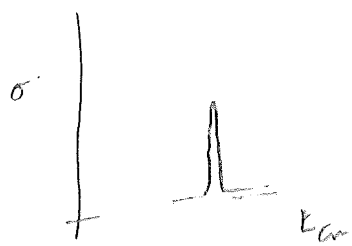
How do we know there are only 3 generations
or specifically $N_\nu = 3$? [expansion of early universe rate depends on # of neutrino species; affects production of primordial ^4He]

Answer: 1990 experiment measuring width of Z.

Z^0 is produced in collisions of e^- and e^+:

$e^-e^+ \to Z^0$ [show Griffiths, fig 9.10]

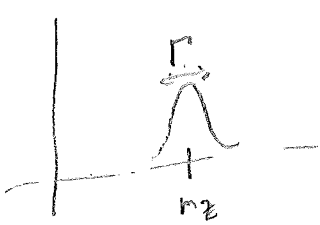
In cm frame, momenta of e^-, e^+ equal & opposite and energies the same, so $E_{cm} = 2E$



When $E_{cm} = m_Z$, Z^0 can be created.

But peak not sharp, has a width, called Γ, that can be measured.

So even if E_{cm} is not quite $= M_Z$ can still be created. Why? Because Z^0 is unstable



Uncertainty principle: there is some uncertainty in energy necessary to create a Z^0

$\Delta p \, \Delta x \sim \hbar$ $\Delta E \, \Delta t \sim \hbar$ (Δt: time over which one measures the energy)

one does not have unlimited time to measure the energy, because Z^0 is unstable, and decays w/ mean life τ, so $\Delta E > \frac{\hbar}{\tau}$. Define width $\Gamma = \frac{\hbar}{\tau}$

$Z^0 \to e^-e^+, \mu^-\mu^+, \tau^-\tau^+, q\bar{q}, \nu\bar{\nu}$

The more types of particle Z^0 can decay into, the shorter it lives & the larger the width. In particular the measurable "width of Z" depends on # of neutrinos (whose mass is $\leq \frac{1}{2} m_Z$)