After recalling the discoveries of the cosmic radiation and of its 'hard' and 'soft' components, the main experiments which clarified the nature and composition of these components are briefly described. As the unique source of high energy particles available before the development of particle accelerators in the 1950's, cosmic rays opened the field of particle physics through a number of fundamental results. These include the demonstration of the existence of antimatter, the development of the lepton concept and of the concept of a universal weak interaction, the discoveries of the charged pion, of strange particles and of hyperfragments. Some of these results, such as those related to the complicated 'history of the muon', are discussed in some detail.
CONTENT OF LECTURES

COVERED PERIOD - 40 YEARS:
FROM DISCOVERY OF COSMIC RAYS (1912)
TO DISCOVERY OF HYPERFRAGMENTS (1953)

ONLY APPROXIMATELY HISTORIC PRESENTATION OF
MAIN IDEAS AND EVENTS THAT PRECEDED THE
DEVELOPMENT OF LARGE ACCELERATORS

ENPHASIS ON ITEMS MOST RELEVANT FOR THE
DEVELOPMENT OF PARTICLE PHYSICS

DETAILS ONLY OCCASIONAL (PERSONAL RECOLLECTIONS)

REFERENCES:

a) The Birth of Particle Physics, based on a Fermilab
Symposium, Edited by L.M. Brown and L.Hoddeson (Cambridge
University Press, 1983).

b) International Colloquium on the History of Particle
Physics, in Journal de Physique, Colloque C8, Supplement
au n° 12, décembre 1982. Specifically: Ch. Peyrou talk
from page C8-7: The Role of Cosmic Rays in the
Development of Particle Physics.

1984

c) Proceedings of "Wingspread Conf. on "50 years of weak
interactions". Specifically: Rochester's report on the
Discovery of the V particle.
THEORY OF AURORA BOREALIS (C. STOEHRER)

HENCE: PRIMARY C.R. ARE CHARGED

DISCOVERY OF COSMIC RAYS etc.

PREHISTORY

1900: STUDY OF CONDUCTIVITY OF AIR BY ELECTROSCOPES
      (J. ELSTER, H. GEITEL, C. T. R. WILSON, ...)

RESIDUAL CONDUCTIVITY PRESENT EVEN AFTER 10 cm Pb SHIELDING.

HYPOTHESIS OF PENETRATING RADIATION OF UNKNOWN EXTRATERRESTRIAL ORIGIN FIRST ADVANCED AS A POSSIBILITY

1909: HYPOTHESIS SOMEWHAT REINFORCED BY THE FACT THAT
      ELECTROSCOPES IN BALLOON AT 4000 m ALTITUDE DISCHARGE MORE
      QUICKLY THAN AT SEA LEVEL (A. GOETEL, ...)

1911-12: V. F. HESS AND SHORTLY AFTERWARDS W. KOLHORSTER

DEMONSTRATE THAT IONIZATION FIRST DECREASES FROM
GROUNDD TO ~700 m, THAN INCREASES STEADILY WITH ALTITUDE.

HESS SHOWS ABSENCE OF DIURNAL EFFECTS AND PUT FORTH
HYPOTHESIS OF EXTREMELY PENETRATING "COSMIC" RADIATION, FOR
MANY YEARS BELIEVED TO CONSIST OF H.E. GAMMAS (GAMMAS FROM
RADIOACTIVE SUBSTANCES KNOWN TO BE FAR MORE PENETRATING THAN
"CORPUScular RAYS"), Penetrating power demonstrated by
measurements under 10 m of water first, 10 m Pb later
INTERRUPTED DURING WORLD WAR I
WORK NOT RESUMED AFTER THE WAR UNTIL - 1922

MILLIKAN PROPOSES THE NAME OF COSMIC RAYS

1927: DISCOVERY LATITUDE EFFECT (J. CLAY)

- 10% MEASURED EFFECT AT SEA LEVEL (A. H. COMPTON et al., 1933)

HENCE: PRIMARY C.R. ARE CHARGED

THEORY OF AURORA BOREALIS (C. STOEHRER)

~5000 hours of calculations and many kg. of paper
for 120 trajectories
MOMENTUM THRESHOLD AT LATITUDE L FOR PRIMARY PARTICLE OF CHARGE $q = z \cdot e$:

$$P_t = 300 \cdot \left( \frac{M^4}{4R^2} \right) \cdot \cos^4 L = 15 \cdot z \cdot \cos^4 L \text{ GeV}$$

BEING $M = |\vec{M}| = \sim 8.1 \times 10^{25}$ gaussxcm$^3$

AND $R = 6.37 \times 10^8$ cm

RESPECTIVELY THE MAGNETIC MOMENT AND THE AVERAGE RADIUS OF THE EARTH.
Fig. 20. - Curva di ionizzazione in funzione dell'altitudine. Il numero degli ioni per c.c. è stato misurato ad una atmosfera; la pressione è misurata in metri d'acqua a partire dalla sommità (1 atm = 10 m. d'acqua).
Fig. 21. - Curva di ionizzazione in funzione dell'altitudine, relativa a Madras (India).
ENERGY SPECTRUM OF PRIMARY COSMIC RAYS

Fig. 26 - Le aree A, B, C di figura 25 sono state utilizzate per calcolare l'energia totale presente nella radiazione a una certa distanza di radiazione. Le aree sono indicate con le aree degli elettroni di energia individuale composta fra V e 2V.

East-West effect predicted by Rossi (1930); observed by T.H. Johnson and by Alvarez and Compton (1933); PRIMARY PARTICLES ARE POSITIVE - Work of M. Schein and others (1940): PRIMARY PARTICLES ARE MOSTLY PROTONS

Primary C.R.'s known today to be composed by

- ~80% protons
- ~15% α particles
- ~5% heavier nuclei + (~1%) e-

With an energy integral spectrum

\[ N(E) = (A+E)^{-n} \]

with \( A \) (of ~1 if E is ~1 GeV) and \( n \) (~2)

change slightly in various energy regions.
HARD AND SOFT COMPONENTS OF COSMIC RAYS NEAR SEA LEVEL

1927: FIRST INVESTIGATIONS OF C.R. WITH CLOUD CHAMBER
FIRST EVIDENCE FOR SHOWER (D.SKOBELZYN, 1928-29)

1928: DEVELOPMENT OF GEIGER-MULLER COUNTER
USING GM-COUNTERS AND PRIMITIVE TIME COINCIDENCES

1929: OBSERVATION OF "ROSSI TRANSITION CURVE" WITH
THICKNESS OF 11 Pb NEAR SEA LEVEL WITH 25 cm Pb PENETRATE AN ADDITIONAL
THICKNESS OF 11 Pb

1930: OBSERVATION OF "ROSSI ELECTROMAGNETIC COINCIDENCES" APPLICATION TO PROVE THAT 60% OF C.R. FILTERED AT
SEA LEVEL WITH 25 cm Pb PENETRATE AN ADDITIONAL
THICKNESS OF 11 Pb

1931: SOFT AND HARD COMPONENTS OF C.R.

1932: COUNTER CONTROLLED CLOUD CHAMBER (P.M.S.BLACKETT AND G.P.S.OCCHIALINI)

1932 ... "THE LUCKY YEAR": DISCOVERY OF THE NEUTRON; FIRST
ARTIFICIAL NUCLEAR REACTION AND

DISCOVERY OF THE POSITRON

COMMUNICATED IN "SCIENCE", SEPTEMBER 1932, BY C.D. ANDERSON,
AS THE OBSERVATION OF "A POSITIVELY CHARGED PARTICLE
COMPARABLE IN MASS AND MAGNITUDE OF CHARGE WITH AN ELECTRON"

1933: PROMPT CONFIRMATION BY BLACKETT AND OCCHIALINI WHO
OBSERVE SHOWERS INITIATED BY NEUTRALS IN THE MIDDLE
PLATE OF THEIR COUNTER CONTROLLED CLOUD CHAMBER, MADE
OF e- AND e+
Fig. 1 The positive electron. The particle comes from the bottom, losing energy in the lead plate. This direction and the one of the magnetic field show that the sign is positive. The ionization is much too weak for a proton.

**Particle comes from bottom as it can only lose energy in traversing the Pb plate**

**Particle is therefore positive**

**Its ionization is much too weak for a proton**

**Its mass is < 20 m_e**

**Conclusive evidence for a new particle (e^+) from 1 event**

(... await until the discovery of the \( \Sigma \), which was expected however from \( \Sigma^+ \))
Fig. 2 A shower coming from the top in the first counter triggered cloud chamber. The overall aspect is symmetric between negative particles (electrons) and positive (positrons) their ionization is too small for protons.

Symmetric aspect of + and -
Ionization too small for protons

Production of $e^+e^-$ pairs could have been discovered with $\gamma$ rays from radioactive sources....
THE DISCOVERY OF THE "MESOTRON"

IT TOOK SEVERAL YEARS.

YUKAWA'S ARTICLE (FEBRUARY 1935) MOSTLY UNKNOWN 1937

\[ N \rightarrow N + y (+, - \text{ or } 0) \]

BETHE + HEITLER: THEORY OF RADIATION WELL KNOWN.

IT PREDICTED ENERGY LOSSES INCOMPATIBLE WITH OBSERVED

PENETRATION OF "HARD" COSMIC RAYS, IF THESE WERE \( e^- \) AND \( e^+ \),

BUT ...

THE TREND WAS TO ASCRIBE THE OBSERVED GREAT PENETRATION OF

C.R. TO BREAK-DOWN OF THE THEORY AT ENERGIES \(-500\) MeV.

SOMEONES THOUGHT THE "HARD" C.R. TO BE PROTONS (+ and -).

PEOPLE RELUCTANT TO ACCEPT NEW PARTICLES WITH NO ROLE ...

UNTIL THE EVIDENCE BECAME UNQUESTIONABLE MOSTLY THROUGH WORK

BASED ON CLOUD CHAMBERS WITH MAGNETIC FIELD.
Counter control cloud chamber in strong H, with plate across the middle for 2 mom. measures ~ 10,000 photos taken at 45º via a.s.e.

Random expans. Striking diff. behaviour of "shower" and "e" p.s.

Fig. 9. Momentum loss of particles penetrating 1 cm of platinum as a function of incident momentum [15].

a) Energy loss \(\Rightarrow\) increasing \(\sim\) linearly for shower part.

b) Showers \(\Rightarrow\) yes for shower particles \(\Rightarrow\) no for single particles

c) Altitude variation: much greater for shower particles

Shower p.s identified as \(\mu^+\) (soft comp.).

Hard component (simple p.s) of \(M \gg m_e\)

Not protons (energy distrib. of knock-on \(e^-\),...)

Mass within \(\sim 100 - 300\) m.e.
Street + Stevenson (1937)

\begin{center}
\begin{tabular}{c}
\textbf{1234}
\end{tabular}
\end{center}

\begin{center}
\textbf{Counter Ctr.}
\textbf{Cloud Chamber}
\textbf{with Pb Plate} \rightarrow
\textbf{and } B = 3,500 \text{ G.}
\textbf{1 s Delayed Exp.}
\end{center}

\begin{center}
\textbf{Track of Negative P.}
\end{center}

\begin{center}
J = 6 \text{ min}^{-1}
H_p = 9.6 \cdot 10^4 \text{ G} \times \text{cm}
\mu = \approx 130 \text{ m}_e \pm 25\%
\end{center}

The track, visible for 7 cm in the chamber, cannot be due to a proton coming from the bottom.

See also: Y. Nishina et al.
\textit{Phys. Rev.} \textbf{52} (1937) 1198

Today value: \( m_\mu = 206.77 \text{ m}_e = 105.659 \text{ MeV} \)
A $\mu^+$ crosses the GM counter inside the chamber and stops in the gas (decay electron not seen). From curvature and range measurements the $\mu^+$ mass is $\sim 240 \text{ m}_{\text{e}}$.
1st direct observation of a $\mu^+ \to e^+$ decay in a high pressure cloud chamber

*Fig. 8 The first mesotron decay photographed in a high pressure cloud chamber by Williams and Roberts.*
ANOMALOUS ABSORPTION OF HARD COMPONENT OF C. R. IN AIR

Nr. of p.p. at sea level smaller than that measured at high altitude with compensating equivalent absorber of dense material

1938: First suggestion that the p.p. are Yukawa unstable particles (Kulenkampff,...)

A mesotron of mass $\mu$, lifetime $\tau$ (at rest) and momentum $p = \beta c \mu \gamma$ ($\gamma = 1/\sqrt{1-v^2}$) has in empty space (~air) a decay mean free path

$$\lambda = \beta c \gamma \tau = p(\tau/\mu)$$

Hence the nr. of mesotrons of momentum $p$ travelling over a length $h$ is attenuated by the measurable factor

$$\exp(-h/\lambda) = \exp(-h/p)(\mu/\tau)$$

And the ratio $\tau/\mu$ can be derived from attenuation measurements if the momentum spectrum of the p.p. is known.
Rossi et al. (1940): $\tau_\mu/m_\mu$

![Graph]

Figure 11.2. Results of the 1939 expedition, showing the decay of mesotrons in air. $N$ is the intensity of cosmic ray mesons and $h$ is the depth. From B. Rossi, N. Hilberry, and J. B. Hoag in Phys. Rev. 57 (1940), 466, Fig. 3.

$$\log N \propto h = \text{atmospheric depth}$$

$N = \text{Intensity of C.R. mesons}$

In 1938 Kulenkampff, Heisenberg, Black et al. had analysed the possibility that certain exps, showing that "mesotrons" were more strongly absorbed by air than by condensed matter, could be interpreted in terms of the instability of the mesotrons ($\tau \approx \mu s$), identified with the "Yukawa particle" (intro. in 1935)

Conclusive exp. & cal evidence for meson instability.

$$\tau_\mu/m_\mu c^2 \approx 2.5 \times 10^{-8} \text{ s/MeV}$$
**DIRECT DETERMINATION OF "MESOTRON" $\tau_\mu$**

**F. RASSETTI (1941)**

---

*Figure 8.1. Schematic of the apparatus used by Franco Rasetti in 1941 to measure the mean life of the cosmic-ray meson. From W. Heisenberg (ed.), *Cosmic Radiation* (N.Y.: Dover, 1946), 88.*

---

**First direct determination of**

$$\tau_\mu = (1.5 \pm 0.3) \mu s$$

*derived from logarithmic decrease for two delays. (Demonstration of exponential decay assumed!)*

**Auger, Maze + Chaminade (1941)**

$$\tau_\mu = (1 \pm 0.3) \mu s$$

*Spurious delays of GM counter pulses, probable cause of small values observed for $\tau_\mu$*
Rossi and Nereson (1942)

Introduction of T. A. C. to measure delays of e\(^+\) from \(\mu^+\) on single \(\mu \rightarrow e\) events.
Rossi and Nercson: Decay curves of C.R. mesons in lead + brass

\[ \tau_\mu = (2.15 \pm 0.07) \mu s \]

1984 value:

\[ \tau_\mu = (2.196 \pm 0.035) \mu s \]

\[ G_F = \frac{192 \pi^3}{m_\mu^5} \frac{1}{\tau_\mu} = 1.03 \times 10^{-5} / M^2_p \]

Fig. 4.7.4. Integral disintegration curves of mesons in lead and brass. Each point represents the observed number, \( N \), of decay events for which the delay is greater than \( t \). From N. Nercson and B. Rossi (NNG43).
First:

$$\tau_\mu = 2.3 \mu s \pm 6.5\%$$

from a best fit through 4 measured points of the decay curve.

(Convinced to be the first to record the expon. decay curve of a free particle
..... total lack of communication with USA)

Next: Test of predictions of Tomonaga + Araki → 0.6 cm thick Fe abs. → OK

Next: Put on magnetic lenses...
THE FOUR EXPERIMENTS MADE IN ROME
(1942 - 1946)

1 - Direct determination of \( \tau_{\mu} \)
   \( \mu^- \)'s stopped in 5 cm thick absorber
   Using especially developed fast delayed coincidences

2 - (Indirect) Test of Tomonaga + Araki predictions
   on behaviour of \( \mu^- \)'s at rest in matte
   \( \mu^- \)'s stopped in 0.6 cm thick absorber (penetrated
   by most of decay electrons of \( \langle \text{range} \rangle \sim 2.5 \text{cm Fe} \))
   (Using same technique)

3 - Direct test of T-A effect in Fe using
   "magnetic lenses" to separate \( \mu^+ \) and \( \mu^- \)
   (Using same technique + lenses)

4 - Direct test of T-A effect in light material (C)
SOME RELEVANT EVENTS IN THE RECENT HISTORY OF ITALY

10 June 1940: Declaration of War to France + England

19 July 1943: Rome bombed by American aircraft

25 July 1943: Fall of fascist government

8 Sept. 1943: Italian separate armistice: start of German occupation

5 June 1944: Allied Troops liberate Rome

25 April 1945: Liberation of Northern Italy
Figure 13.5. Rossi-Pucciani lenses. The side view (at top) shows the trajectory of a "wanted" charge sign (solid line) and of an "unwanted" one. The top view shows the direction of the magnetic field and the position of the top Geiger-Muller counter. From B. Rossi, in Nature 126 (1931), 300.

Developed by Rossi "on a principle suggested by prof. L. Pucciani." (Nature 126 (1931) 300)
Top lens (A) used to alterate nearly equal charge distribution of C.R.'s at sea level.

Bottom lens (B) used to analyze altered charge distribution, by making its $\tilde{B}$ either $\uparrow\uparrow$ or $\uparrow\downarrow$ with respect to that of the top lens.

Strong effect ($\sim 35\%$) observed by comparing coincidences (1, 2, 3) with $\uparrow\uparrow$ and $\uparrow\downarrow$ configurations.
Red curve: Energy spectrum of C.R. mesons at sea level computed assuming a primary power spectrum $E^{-n}$ ($n = 2.83$) and $\tau_{\mu}/m_{\mu}c^2 = 2 \times 10^{-8}$ s/MeV

True curve (cc): Energy spectrum as emerging from the "lens doublet" for parallel $\vec{B}$ (17.2 kgauss) in the two magnetic lenses.

Another curve (cd): Energy spectrum for anti-parallel $\vec{B}$ in the two magnetic lenses.
$\tau_\mu / m_\mu c^2 \approx 2.1 \times 10^{-8} \text{ s/MeV} \pm 20\%$

Today's value: $\tau_\mu / m_\mu c^2 = 2.0733 \times 10^{-8} \text{ s/MeV}$
Main ingredient: "fast delayed coincidences" using Piccioni's "series coincidences" with secondary emission tubes (EE50)

<table>
<thead>
<tr>
<th>SIGN</th>
<th>Absorber</th>
<th>Decays/100 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>5 cm Fe</td>
<td>67 ± 6.5</td>
</tr>
<tr>
<td>_</td>
<td>&quot;</td>
<td>3</td>
</tr>
<tr>
<td>+</td>
<td>4 cm C</td>
<td>36 ± 4.5</td>
</tr>
<tr>
<td>_</td>
<td>4 cm C + Fe</td>
<td>27 ± 3.5</td>
</tr>
</tbody>
</table>

μ⁻ decays at rest. Cannot be Yukawa part.
MODEL OF EXPERIMENT
C/O Smithsonian Museum

GM COUNTER
MAGNETIC LENS
GRAPHITE REAS
CHOICE OF CARBON ABSORBER
(in my personal recollections)
To extend check of theor. predic.s
to low Z (see large $\frac{1}{2}/Z\varepsilon^2m_\mu$)
To search for possible $\gamma$ from
$\mu^{-}$ capture (later done by Piccioni in USA)
To clarify uncertain indication
of previous exp. in Al (Maze + Chaminade) that $>\frac{1}{2} \mu^{-}$ decay

MEANING + CONSEQUENCES OF EXPERIMENT
Discrepancy of $10^{12}$ with theor. predic.s
(Fermi, Teller + Weisskopf, 1947)
Two-meson hypothesis (Marshall + Bethe, 1947)
$\varepsilon^4$ "Wheeler law" (Wheeler, 1947)
Idea of Univ. Fermi Interaction (Pontecorvo, 1947)
Tiomno + Wheeler, 1948; Puppi; Klein, 1948; ......) $\rightarrow$ $\varepsilon$
Start of new field of "mesonic atoms"
c.R. meson as "heavy e" (2nd charged lepton)
$\rightarrow$ discovery of $\varepsilon$ (Perl et al.)
High energy $\mu$ scattering (e.g. E. Amaldi, G. Fissareo, etc.)
Z-DEPENDENCE of $\mu^-$ CAPTURE

"MESIC ATOM" FROM $\mu^-$ CAPTURE IN $K$-ORBIT AROUND
NUCLEUS $Z, A$ HAS RADIUS

$$\Gamma_\mu = \hbar / 2 \mu e^2 = \sim 250 / Z \text{ fermi}$$

(muon mass)

IN LIGHT ELEMENTS ALWAYS $\Gamma_\mu \gg \Gamma_{\text{nuc.}} = \sim 1.75 \sqrt{Z} \text{ fermi}$

SO THAT $\psi$ (at nucleus) $\approx \psi(0) \cap Z^{3/2}$

HENCE THE CAPTURE PROBABILITY

$$\Lambda_c = \frac{1}{\tau_c} = \sim |\psi|^2 \cdot \Gamma_{\text{nuc.}} \cap Z^{3/2} = Z^4 \quad \text{(WHEELER)}$$

CAN BE WRITTEN AS

$$\frac{1}{\tau_c} = \frac{1}{\tau_\mu} \left( \frac{Z}{Z_0} \right)^4 \quad \text{WITH } Z_0 \text{ EMPIRICALLY } = \sim 11$$

(muon lifetime)

THE PROBABILITY OF DISAPPEAR. OF $\mu^-$ AT REST IS THEN

$$\Lambda_\text{-} = \frac{1}{\tau_c} = \frac{1}{\tau_\mu} + \frac{1}{\tau_c} = \frac{1}{\tau_\mu} \cdot \sqrt{1 + \left( \frac{Z}{Z_0} \right)^4} \quad \text{(COMPETING PROBABILITIES)} \quad \text{(TICHO; ROSSI+VALLEY)}$$

FRACTION OF SPONT. DECAYS

$$\frac{1}{\tau_\mu} / \frac{1}{\tau_c} = \frac{\tau_\text{-}}{\tau_\mu} = \frac{1}{\sqrt{1 + (Z/Z_0)^4}} = \left\{ \begin{array}{ll}
92\% \text{ in } C \ (Z=6) \\
6\% \text{ in } Fe \ (Z=26) 
\end{array} \right.$$  

IN AGREEMENT WITH EXPERIMENTS
WORK AT BRISTOL WITH
NUCLEAR EMULSION
as commercially developed by Ilford Co., with Powell + Occhialini

LATTES, MUIRHEAD, OCCHIALINI, POWELL
(Nature, May 1947)

soon after observation (by Perkins and by Occhialini + Powell) that cosmic ray mesons "can enter nuclei" of emulsion exposed at high altitude "and produce disintegrations with the emission of heavy particles"

Mass of slow particles, derived from grain counting and range in emulsion calibrated with fast protons, led to recognition a "meson", which combined with multiple scattering measurements

Out of 65 meson stopping in emulsion 2 give rise to the emission of a secondary meson $m_2 \rightarrow m_1$
First Two Examples of $\pi \rightarrow \mu$ Decays

(May 1947)

Fig. 10 The first published $\pi, \mu$ decay.

Fig. 11 The second $\pi, \mu$ decay. The $\mu$ quits just before stopping but is clearly at the end of its range.
"$9$-mesons" interpreted as $\pi^0$ ($\mu$-mesons) entering and stopping ineffectively in the nuclear material.
"$\sigma$-mesons", interpreted as $\pi^-$ mesons captured in matter at the end of their range, where they produce a "star".
Fig. 4.8.1. Mosaic of microphotographs showing a $\pi \rightarrow \mu$ decay in Ilford C2 emulsion. From Lattes et al. (LCM47.1).

Fig. 4.8.2. Mosaic of microphotographs showing a $\pi \rightarrow \mu \rightarrow e$ decay. Kodak NT4 electron-sensitive emulsion. From Brown et al. (BR149.2).

Discovery of $\pi^+ \rightarrow \mu^+$ decays

constant range

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

$\rightarrow (e^+ + \nu_e + \bar{\nu}_\mu)$
This table reproduces table I of the original publication of Lattes, Occhialini, Powell. It shows that the secondary $\mu$, have a unique range in the $\tau$, $\mu$ decay.

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Range in emulsion in microns of Primary meson</th>
<th>Range in emulsion in microns of Secondary meson</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>133</td>
<td>613</td>
</tr>
<tr>
<td>II</td>
<td>84</td>
<td>565</td>
</tr>
<tr>
<td>III</td>
<td>1040</td>
<td>621</td>
</tr>
<tr>
<td>IV</td>
<td>133</td>
<td>591</td>
</tr>
<tr>
<td>V</td>
<td>117</td>
<td>638</td>
</tr>
<tr>
<td>VI</td>
<td>49</td>
<td>595</td>
</tr>
<tr>
<td>VII</td>
<td>460</td>
<td>616</td>
</tr>
<tr>
<td>VIII</td>
<td>900</td>
<td>610</td>
</tr>
<tr>
<td>IX</td>
<td>239</td>
<td>666</td>
</tr>
<tr>
<td>X</td>
<td>256</td>
<td>637</td>
</tr>
<tr>
<td>XI</td>
<td>81</td>
<td>590</td>
</tr>
</tbody>
</table>

Mean range $614 \pm 8 \mu$. Straggling coefficient $\sqrt{\sum \Delta_i^2 / n} = 4.3$ per cent, where $\Delta_i = R_i - R$, $R_i$ being the range of a secondary meson, and $R$ the mean value for $n$ particles of this type.
Fig. 4.9.5. Disintegrations produced by the nuclear absorption of negative $\pi$-mesons. 
(a) D. H. Perkins, Ilford B1 emulsion (PDH47). (b) Powell, Ilford C2 emulsion (PCF49).

q) First observations of nuclear disintegration from $\pi^-$ absorption in emulsion observed by Perkins in 1947
Four examples of the decay sequence

\[ \pi \to \mu \to e \]

as observed in electron sensitive nuclear emulsions.
CONCLUSIONS from "EMULSION WORK"

1) There are two mesons: \( \pi \) and \( \mu \)

2) \( \pi \to \mu + \gamma \) because \( R_\mu = \text{cost} \).

3) Best interpretation of Rome exp. is to assume that \( \pi \) is the "Yukawa particle".

4) If the \( \pi \to \mu \) decay is fast enough, the back of p.p. C.R. are \( \mu \)'s.

5) Mesons producing stars (\( \sigma \)) are \( \pi^- \)'s.

6) Mesons stopping in emulsion uneventfully (\( \rho \)) are \( \mu^+ \) or \( \mu^- \) (decay electrons still same observable).

So everything O.K.? The Yukawa particles have been found, even though with other properties than expected (it decays into a \( \mu \), NOT into an \( e^\pm \); Yukawa theory does not explain \( \beta \) decay?).

What about the \( \mu \)?

Which role plays it in particle physics?

"Who ordered it?"
GENESIS of concept of Universal Fermi Interaction.

June 47 (before pion discovery):

Pons corvo points out that because of the result of the Rome experiment:

- The Yukawa theory of $\beta$ decay is untenable
- $\beta$ decay is to be described as originally proposed by Fermi ($4$-fermion interaction)
- $\beta$ decay and muon capture have the same strength if allowance is made for phase space and size of Bohr orbit.
- The muon has spin $1/2$ and is absorbed with the emission of one neutrino ($\mu^- + p \rightarrow n + e^-$)
- Perhaps $\mu \rightarrow e + \gamma$ (a process later searched for together with Hincks)

This is the first presentation of the concept of Universal Fermi interaction elaborated with subsequent contributions from Klein, Puppi, Tomino and Wheeler, etc.

What about muon decay?
On the Range of the Electrons in Meson Decay

J. Steinberger
The Institute for Nuclear Study, University of Chicago, Chicago, Illinois
(Received January 10, 1949)

Fig. 8. The experimental points represent the data obtained in Chicago and on Mt. Evans. The indicated error is the standard deviation. The full curves 1 and 2 represent the calculated absorption curves for 50 and 25 Mev, respectively. Curve 3 is the absorption curve calculated for electrons emitted in a continuous spectrum. The spectrum is calculated from Eq. (2), taking $\mu = 100$ Mev.
Energy spectrum of $e^+$ from $\mu^+$ decay

![Graph of the energy spectrum of $e^+$ from $\mu^+$ decay.](image)

Fig. 13 The first spectrum of the electron energy in $\nu$, $e$ decay obtained in a cloud chamber. (As we know now the curve dips much too much towards zero at the high energy end, but the measured points demonstrate clearly the existence of a spectrum).

Steinberger (1948)

Hinks + Pontecorvo (1948)

Leighton, Anderson + Serif (1949)

Demonstration of a three body decay

Absence of $\mu^+ \rightarrow e^+ \gamma$ (Hinks + Pontecorvo)

Absence of $\mu^- p \rightarrow n^- \gamma$ (Ficconi)

Absence of $\mu^- n \rightarrow N^- e^-$ (Lagarrigue + Peyrou)
...END OF TANGLED TALE OF \( \mu \)

First observed as constituent of the hard component of cosmic rays.

Then as an unstable particle of intermediate mass.

For long erroneously identified with Yukawa mediator of short range nuclear force.

Subsequently recognized as a sort of "heavy e"—the first heavy lepton in today's words—subject to weak processes of spontaneous decay and nuclear capture quite similar to \( \beta \) decay (U.F.I.)

Finally found as daughter particle of a strongly interacting particle—\( \pi^0 \)—today known as the lightest quark-antiquark structure apparently existing in nature.

Subject to a weak three body decay

\[ \mu \rightarrow e \nu \nu \]
DISCOVERY OF V-PARTICLES

POSITIVE PARTICLE OF MASS 990 \( m_e \pm 12\% \) AS DERIVED FROM THE COLLISION, SUPPOSED ELASTIC, WITH AN \( e^- \) OF THE GAS OF A CLOUD CHAMBER (LEPRINCE RINGUET, LHERITIER, 1944).

V-PARTICLE WORK AT MANCHESTER GREW OUT OF AN EXPERIMENT DESIGNED TO INVESTIGATE CREATION OF P.P. BY COUNTER TECHNIQUE (JANOSSY AND INGLERY, 1939).

CLOUD CHAMBER INCORPORATED ALLOWED TO CONCLUDE IN 1943 (IN AGREEMENT WITH SCHEIN'S CONCLUSIONS, - 1940) THAT THE "PENETRATING SHOWERS" WERE ORIGINATED BY PRIMARY PROTONS + NEUTRONS.

END OF THE WAR - BLACKETT BACK IN MANCHESTER SUPPORTS IMPROVEMENTS OF CLOUD-CHAMBER SYSTEM.

ROCHESTER AND BUTLER UTILIZE BIG "BLACKETT MAGNET" AND NEW CLOUD CHAMBER WITH 3 cm Pb PLATE ACROSS.

1\(^{st}\) \( V^- \) EVENT OBSERVED IN OCTOBER 1946 (\( K^- \) DECAY)
1\(^{st}\) \( V^+ \) EVENT - " MAY 1947 (\( K^+ \) DECAY)

BOTH APPEAR AS DECAY IN FLIGHT OF SHORT LIVED PARTICLES OF ESTIMATED MASS - 1000 \( m_e \) (IF NO NEUTRALS EMITTED IN \( V^- \) DECAY)
Fig. 1. – Prima fotografia di evento $V^*$ ottenuta da Rochester e Butler, nel 1947, con camera di Wilson immersa in campo magnetico di 3500 gauss. Poche millimetrici al disotto della lastra contenuta nella camera una particella neutra decade in volo in due particelle cariche che producono le due tracce $V^*$ visibili nella parte destra inferiore della foto. [Fotografia riprodotta per gentile concessione del prof. G. D. Rochester].

- No blob of recoil nucleus at vertex of $V$
- However small the mass of the secondary $p$. is assumed to be, the mass of the primary is $> 800 \text{ me}$
- If the secondary $p$. are mesons then $m_{\text{prim.}} \approx 1000 \text{ me}$

First example of $K^0 \to \pi^+ + \pi^-$
First \( V^+ \) EVENT \( (\text{observed by Rochester and Butler on May 1947}) \)

Fig. 15 The first \( V^+ \) is visible to the right of the top part of the chamber, the secondary crosses the lead plate.

Essentially same arguments and same conclusions valid for previous \( V^0 \) event. This is the first example of \( K^+ \) decay.

\(~2\) years elapse before observation of next event observed \( (\text{with nuclear emulsion of improved quality by the Bristol Group, 1949}) \)
A heavy particle (K), but lighter than a proton, stops in emulsion \( (m_K \sim 1000 \text{ m}_e \text{ from ionization range} + \text{ scattering range}) \). Three coplanar tracks arise from the stop: one due to a slow \( \pi^- \) which stops producing a "star"; the other due to mesons (\( \mu \)'s or \( \pi \)'s) as seen from measurements of ionization and scattering. If the three secondaries are pions then

\[
m_K \sim 985 \text{ m}_e
\]
DISTINCTION BETWEEN $\Lambda^0$ AND $K^0$ (I)

Achieved through work carried out in the early 1950's with large magnetic cloud chambers by

Manchester Group (Armenteros et al.) at Pic du Midi
Caltech Group (Leighton et al.)
Indiana Group (Thompson et al.)
Berkeley Group (Fretter et al.)
M.I.T. Group (Bridge et al.)

Mostly reported at the Bagnerè de Bigorre Conference

The Caltech group (Anderson group) was the first to confirm the discovery of Rochester and Butler reporting 34 similar events ($\nu$ particles)

The Manchester group moved the apparatus on the Pic du Midi in 1950 and in March 1951 reported the observation of 36 $\nu^0 + 7 \nu^\pm$. In 4 of the 36 $\nu^0$ the positive track appeared to be very likely that of a proton; the negative one that of a meson

(next transparencies)

In some cases, however, the positive particle was clearly lighter than a proton. Here were the first indications for the decay modes $\nu^0 \rightarrow \rho \pi^-; \nu^0 \rightarrow \pi^+\pi^-$ only later established definitively.
FIRST EXAMPLE OF $\nu_2^o$ DECAY ($\Lambda^0 \rightarrow p + \pi^-$)

Fig. 17 The first $\nu_2^o$, the heavy ionization of the positive is clearly seen.

FROM EXPOSURE AT PIC DU MIDI
(ARMENIERTES et al. 1954)
EXAMPLE OF $V_o \rightarrow p + \pi^-$ OBSERVED AT CALTECH
BY LEIGHTON et al. (1953)

Fig. 3. – Esempio di evento $V_o$ ottenuto da Leighton et al. con camera di Wilson in campo magnetico di 5000 gauss. La particella positiva (a destra) è identificata per un protone; la massa di quella negativa (a sinistra) è compresa tra 230 e 430 m$_\pi$ [21].

[Fotografia riprodotta per gentile concessione del prof. C. D. Anderson].
The positive secondary cannot be a proton; from curvature and ionization measurements its mass is \( m_{\pi} \) providing evidence for the decay scheme

\[
\nu_2^* (\kappa^0) \rightarrow \pi^+ \pi^-
\]
DISTINCTION BETWEEN \( \Lambda^0 \) AND \( K^0 \) (II)

a) Use of parameter \( \alpha' = (p_1^2 - p_2^2)/(p_1^2 + p_2^2) \)

introduced by Armenteros + Bodolansky. To test level of symmetry in decay

\[ \Lambda \rightarrow m_1 + m_2 \]

Since

\[ \alpha = \frac{m_1^2 - m_2^2}{\beta M^2} + \frac{2 p^x \cos \theta^x}{M} \]

\[ \bar{\alpha} = 0 \text{ only if } m_1 = m_2 \]

Results from expos. at Pic du Midi provided first evidence for two groups of events:

1) events giving \( \bar{\alpha} = 0.69 \) \( (V_1^0 \rightarrow \pi^+ \pi^- ; Q = 37 \text{ MeV}) \)
2) \( \bar{\alpha} = 0 \) \( (V_2^0 \rightarrow \pi^+ \pi^- ; Q = 214 \text{ MeV}) \)

Although it was not yet proved that they came indeed from two different particles as indicated [A unique neutral particle undergoing the decay modes \( \rightarrow p + \pi^- \) neutral, \( \rightarrow n + \pi^+ + \pi^- \) could not be excluded]

Proof of a two-body decay \( (V_1^0 \rightarrow p + \pi^- + (37 \pm 2) \text{ MeV}) \)
reported at 3rd Rochester Conf. by H.C.T. group

b) Use of Thompson \( P_x (\alpha) \) ellipses and \( Q \)-surface

High accuracy results presented at Bagnière de Bigorre conclusion that there are particles of same mass \( \sim 965 m_e \) with different decay modes. Here initiated the "\( \beta \)-puzzle" which ultimately led to the recognition of the BREAKDOWN OF LATTICE CONSERVATION IN WEAK INTERACTIONS
Fig. 19 The l/p, a plot of the Manchester events. The grouping in two decay modes is clearly seen.
Fig. 22 The $\alpha$, $p_T$ plot of Thompson. The grouping on the ellipses of two-body decays for the $V_2^0$ and $V_2$ is evident. One point in the middle is a first example of anomalous $V_2^0 (K_L^0)$. 

First example of anomalous $V_{2}^{a} (K_{L}^{0})$.
CHARGED STRANGE PARTICLES

Discovery of \( \Xi^- \) \((\rightarrow \Lambda^0 \pi^- \rightarrow p \pi^-)\)

Fig. 23 A geometric reconstruction of the first \( \Xi^- \) (cascade particle) photograph taken at the Pic du Midi by the Manchester group. (1952)

\[ \Xi^- \rightarrow \Lambda^0 + \text{meson} \]

(Decay point of \( \Xi^- \) in plane of secondary of \( \Lambda^0 \))

Three similar events reported at Cagnère de Bigorre by Leighton provided conclusive evidence for the existence of this negative "cascade hyperon" (a negative baryon)?
FIRST EXAMPLE OF $\Sigma^+ \to p + \pi^0$

[MILAN + GENOA Group, Nov. 1953]
(Bonetti et al.)

![Diagram showing particle trajectories and mass information.](image)

Fig. 24 The first $\Sigma^+ \to p + \pi^0$ recorded in emulsion by the Milano, Genova Group.

Previous example of possible "superprotons" already reported at Bagneres de Bigorre, without providing conclusive evidence. Mass of $\Sigma^+$ much too large to consider $\Sigma^+$ as an isospin partner of the $\Lambda^0$. 

$\varepsilon [\Sigma^+ \to \pi + \pi^+]$
Fig. 25 The first hyperfragment. The track f is a heavy fragment which thins down at the end of its range and then explodes. The explosion is due to the decay of a bound $A'$. 
STRANGE PARTICLES IN COSMIC R. (a summary)

1946 Rochester + Butler \( \nu^0 \rightarrow \nu_2^0 \rightarrow \theta^0 \Rightarrow K_2^0 \rightarrow \pi^+ \pi^- \)  
Mag. Cl. Ch.

1947 "  "  "  "  "  "  "  "  "  "  "  "

1949 Bristol group \( c \Rightarrow K^+ \rightarrow \pi^+ \pi^+ \pi^- \)  
Emulsion

1951 Manchester gr. \( V_2^0 \Rightarrow \Lambda^0 \rightarrow p \pi^- \)  
Mag. Cl. Ch.

1951 O'Ceallaigh \( K \Rightarrow (K\mu_3) \)  
Emulsion

1951 "  "  "  "  "  "  "  "

1951 \( K^+ \Rightarrow (K\mu_2) \)  
"  "  "  "  "

1952 Manchester gr. CASCADE PART. \( \Xi^- \rightarrow \Lambda^0 \pi^- \rightarrow p \pi^- \)  
Mag. Cl. Ch.

1953 Thompson ANOMALOUS \( V_2^0 \Rightarrow K_2^0 \rightarrow \pi^+ \pi^- \pi^0 \)  
"  "  "  "  "

1953 Milan Genda gr. SUPERPROTON \( \Sigma^+ \rightarrow p \pi^0 \)  
Emulsion

1954 Henon + O'Ceallaigh \( \chi \Rightarrow (K\pi_2) \)

Discoveries ~ equally shared between two techniques: Magnetic Cl. Chamber and Nuclear Emulsion
Concluding Remarks

Of two reasons for high em. in particle phy.

a) creation of new particles
b) exploitation of microscopic structure by probing distances of ~cm/E

Only a) exploited in Cosmic Rays

Nevertheless cosmic rays opened the field of particle physics through

First discovery of antimatter — the positron
Discovery of new e.m. processes — pair production
Discovery of cascade processes — e.m. cascade
Discovery of first "heavy lepton" — the muon
Concept of universal Fermi interaction
Discovery of first "Yukawa meson" — the pion
Discovery of new layer of hadronic matter:
    Strange particles + hyperfragments

All that done by singles or small groups, with limited financial support, with no other than the "intellectual pressure" of knowing nature, in a "family style" type of work belonging to an era where no need of "managerial talent"