Luciano Maiani:
Lezione Fermi 6
Nuove particelle negli anni ’50 e’60, un’esplosione demografica

Sommario

1. Le Particelle “strane”
2. Quali particelle sono “elementari”?
3. Il mondo delle risonanze
4. La Democrazia Nucleare
5. Costituenti: primi tentativi
6. Simmetrie imperfette

1. Le particelle "strane"

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The Discreet Charm of the Nuclear Emulsion Era

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- La scoperta delle particelle strane e i tempi eroici della ricerca coon le emulsioni nucleari sono raccontati in questo bell'articolo di Milla Baldo Ceolin, scomparsa l'anno scorso. Lo consiglio a tutti !

evento V^+= una particella carica decade in volo in una particella carica ed una neutra

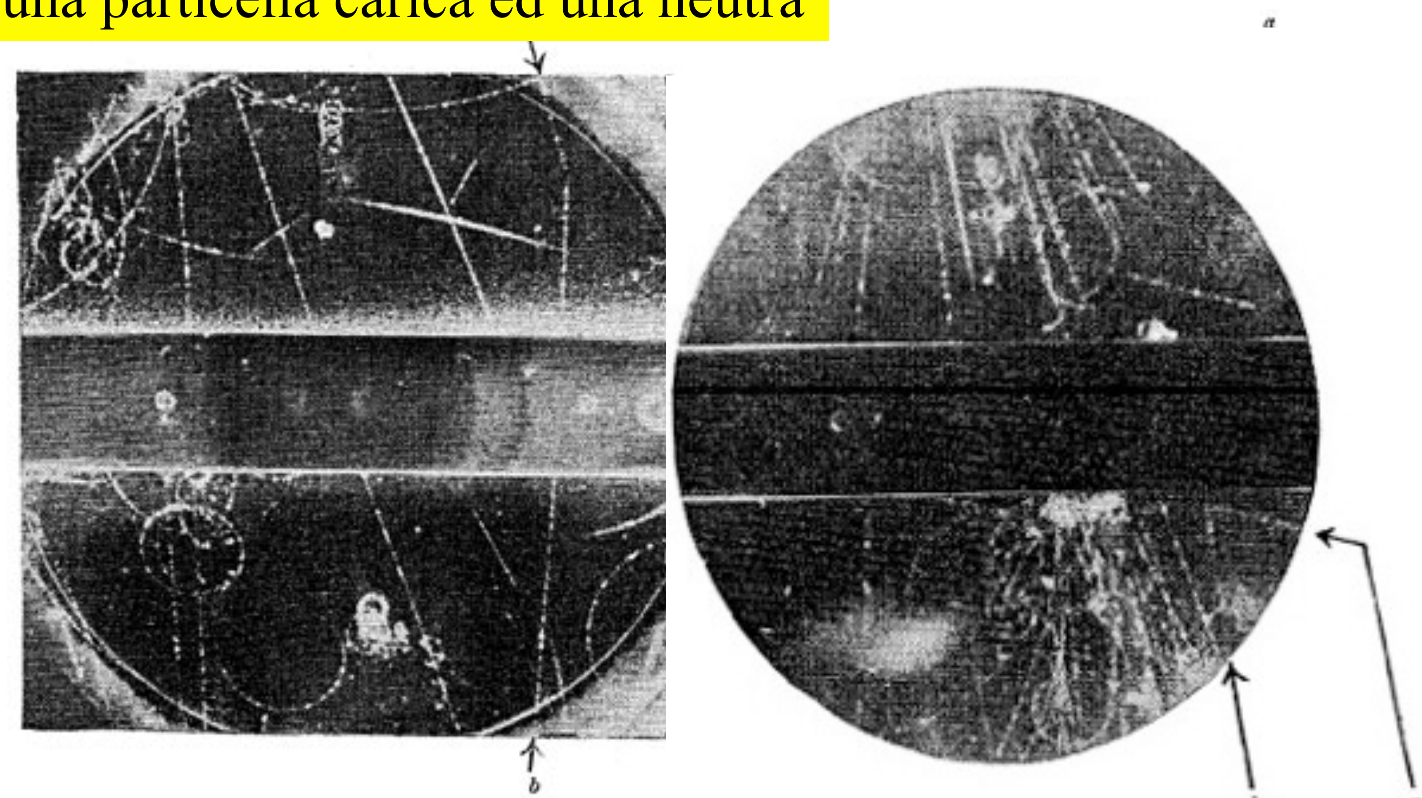
Nature **160**, 855-857 (1947)

Evidence for the existence of new unstable elementary particles

By Dr. G. D. Rochester & Dr. C. C. Butler

Physical Laboratories, University, Manchester

•massa particella madre circa 500 MeV



evento V^0= una particella neutra decade in volo in due particelle di carica opposta

first classification of strange particles

Classification by L. Leprince-Ringuet (1953)

GROUPS OF PARTICLES

1. *L-mesons(symbol L): π-meson, μ-meson, any other possible lighter meson.*
2. *K-mesons* (symbol *K):* particles with mass intermediate between those of the π-meson and the nucleon.
3. *H-particles: hyperons (symbol H): particles with mass intermediate between* those of the nucleon and the deuteron. This definition to be revised if "fundamental" particles heavier than the deuteron are found.

PHENOMENOLOGICAL DESCRIPTION

4. *V-event*: phenomenon which can be interpreted as the decay in flight of a K-meson or a hyperon. Subclasses V^0 and $V^{\pm}$.
5. *S-event*: phenomenon which can be interpreted as the decay or the nucleon capture of a K-meson or a hyperon at rest.

New particles, mass (MeV) and decays then observed (cloud chambers and emulsions) :

$K^0(498) \rightarrow \pi^+ \pi^- (V^0)$

$K^{\pm}(494) \rightarrow \pi^{\pm} \pi^0 (V^{\pm})$, $\pi^{\pm} \pi^+ \pi^-$.

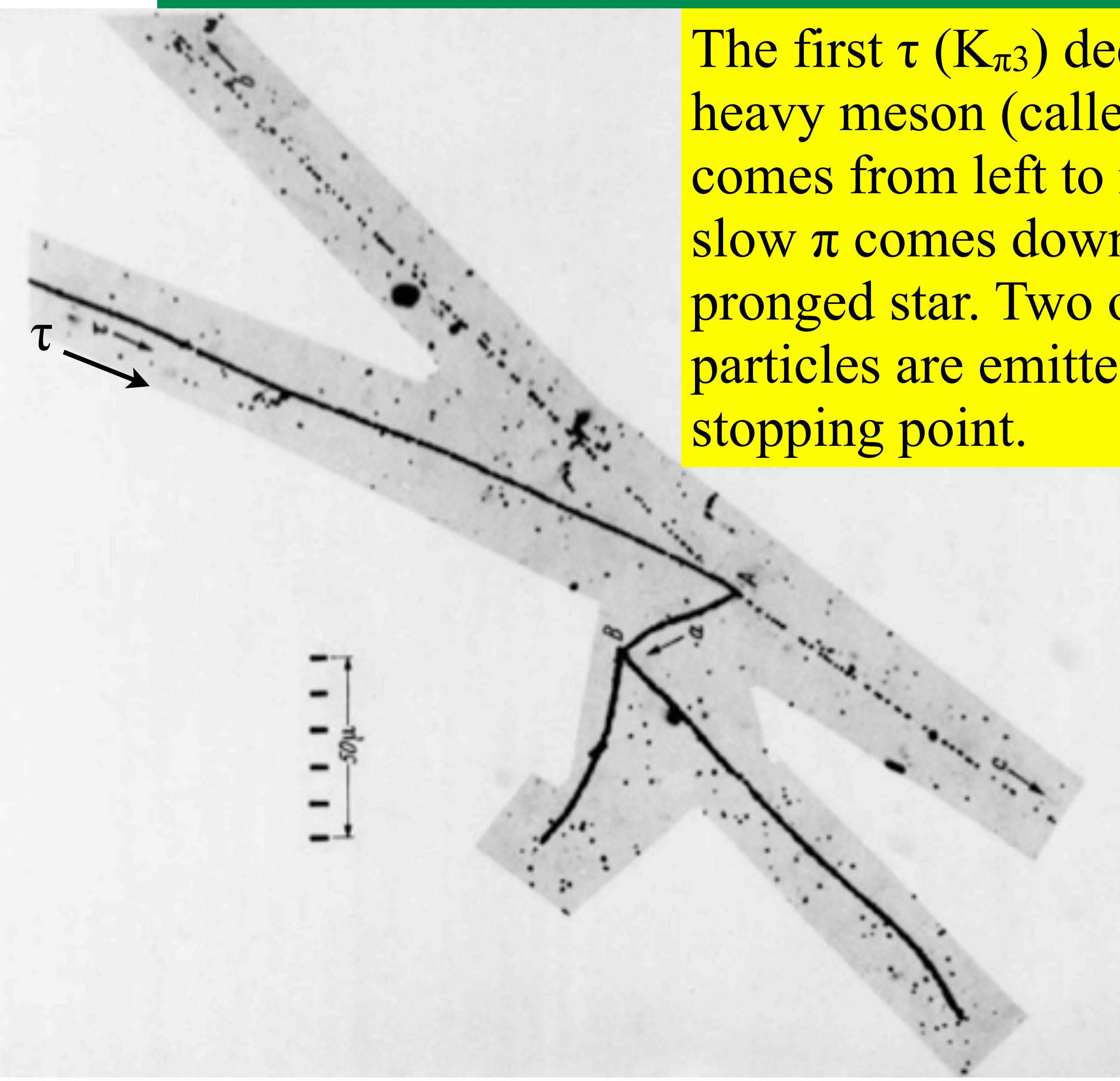
$\Lambda^0 \rightarrow p\, \pi^- (V^0)$;

$\Sigma^+ \rightarrow p\, \pi^0$, $n\, \pi^+ (V^+)$;

$\Xi^- \rightarrow \Lambda^0\, \pi^- (V^-)$.

Stella nucleare

il primo evento di decadimento $K \to 3\pi$ (Bristol, 1948)



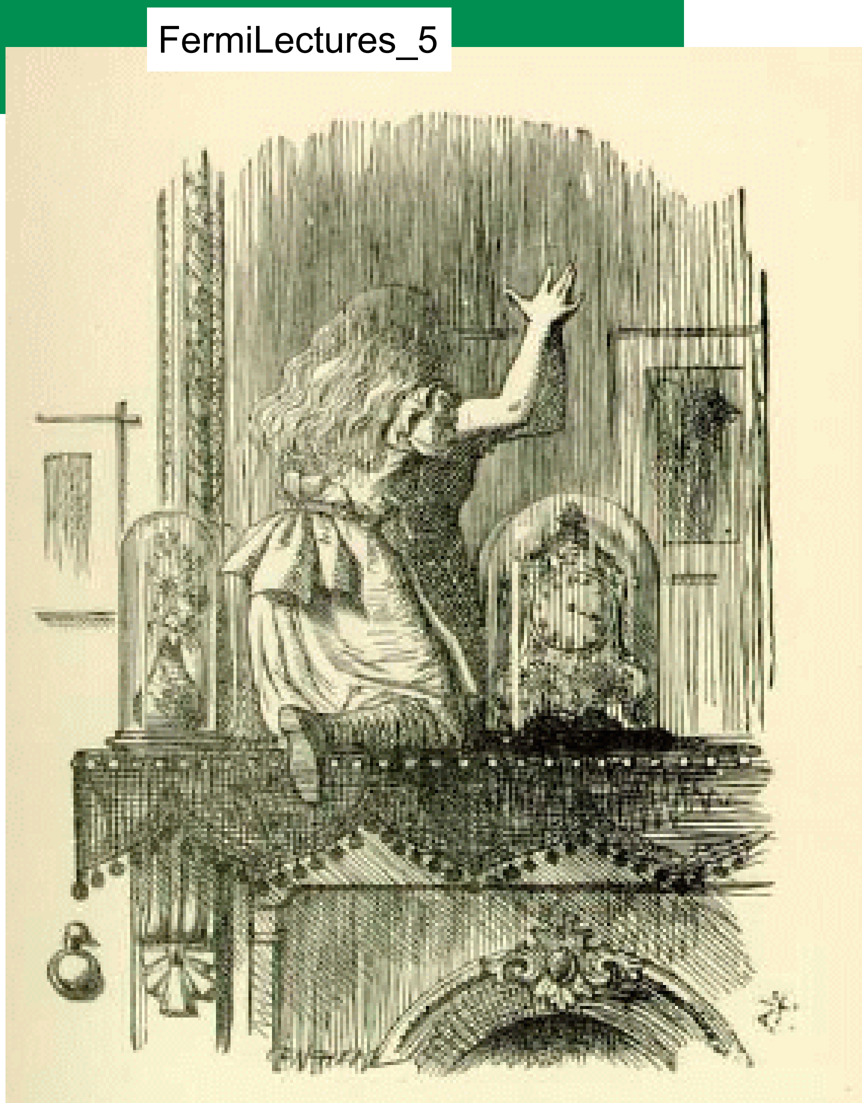
The first τ ($K_{\pi 3}$) decay: the primary heavy meson (called τ in the picture) comes from left to right and stops. A slow π comes down and makes a two-pronged star. Two other lightly ionizing particles are emitted from the first stopping point.

Figure 3 Beppo Occhialini talking in favor of the G-stack exposure at the Pisa Conference. Pisa, 1955. Accanto a Beppo, Bruno Touschek.

perche' "strane"?

- sono prodotte in abbondanza (dalle interazioni forti)
- ma hanno vita media lunga, tipica delle interazioni deboli
- il comportamento e' stato interpretato, indipendentemente, da Murray Gell-Mann e da Kazuhiko Nishijima come legato all'esistenza di un nuovo tipo di carica, la "stranezza", S, conservata nelle interazioni forti ma non nelle interazioni deboli
- S=0 per protone, neutrone e pione, ma $S \neq 0$ per K e iperoni
- Le particelle strane sono prodotte in coppia (ad es. una con S=+1, l'altra con S=-1, quindi $S_{tot}=0$, come lo stato iniziale protone+nucleo) ma ciascuna deve decadere in particelle con S=0, cosa che puo' avvenire solo con l'interazione debole, quindi vivono a lungo;
- lo schema regge se possiamo dare a tutte le particelle strane dei valori di S che rispettano queste regole (es. $S(\Lambda, \Sigma)=-1$, $S(K^0, K^+)=+1$, $S(\Xi)=-2$,...), come infatti si verifica.

violazione della Parita'



- due particelle neutre con massa molto simile hanno decadimenti diversi: $\theta \rightarrow 2\pi$; $\tau \rightarrow 3\pi$
- l'analisi dei decadimenti mostra che gli stati finali hanno spin 0 ma proprieta' opposte per riflessione

$$\theta \to +\theta;$$

$$\tau \to -\tau$$

- un esempio sarebbero le due quantita' scalari costruite con vettori:

$$(\mathbf{v} \cdot \mathbf{w}) \to +(\mathbf{v} \cdot \mathbf{w})$$

$$(\mathbf{v} \times \mathbf{z}) \cdot \mathbf{w} \to -(\mathbf{v} \times \mathbf{z}) \cdot \mathbf{w}$$

- soluzione del θ-τ puzzle (T.D. Lee, C. N. Yang, 1956): θ e τ sono modi di decadimento della stessa particella (un K^0) ma la simmetria per Parita' non si conserva nei decadimenti deboli
- la "casa nello specchio" e' diversa!

Milla's recollections, Venice Conference 1957 (Adv. in Nucl.& Part. Phys.)

Figure 5 The Padova-Venice Conference in 1957. A rest in the area of the San Giorgio isle in Venice. From left to right: B. Touschek, T.D. Lee, W. Pauli, and R. Marshak.

At the Venice Conference, .. Jack Steinberger presented evidence for parity nonconservation in Λ^0 decay...in purely hadronic interactions.
A large theoretical participation...
T.D. Lee gave a talk on weak interactions...the two-component ...neutrino theory and ... lepton conservation; Bruno Touschek, ...proposed that a suitable gauge transformation of the neutrino field, imposed to keep $m_\nu = 0$, leads to two-component neutrinos; moreover, he elaborated on the equivalence of two-component and Majorana neutrinos.
One of the most successful theoretical models...was the one presented by Robert Marshak and George Sudarshan, leading to the universal *V-A* theory—another triumph for the Fermi theory.

Marshak & Sudarshan stated, contrary to the then-current experimental evidence, that all weak interactions are of type *V-A* with $G_V \simeq G_A$, ..lepton conservation is incorporated, neutrinos are two-component spinors and all particles participate in the weak interactions in the same two-component manner.
Here also came the suggestion that the weak interactions arose from the exchange of charged vector bosons, the $W^{\pm}$.

Particlle elementari, ma quali ?

THE
PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 76, No. 12 DECEMBER 15, 1949

Are Mesons Elementary Particles?

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(Received August 24, 1949)

IN recent years several new particles have been discovered which are currently assumed to be "elementary," that is, essentially, structureless. The probability that all such particles should be really elementary becomes less and less as their number increases.

muon
strange particles
Δ^{++}
.....

composite by "constituents" which are more elementary ?

S-matrix, bootstrap, nuclear democracy?
particles are all on an equal footing: poles in S-matrix, solutions of self-consistency equations

Fermi&Yang's proposal:

$$\pi^+ = p\bar{n}$$

related by a large symmetry? possibly including spin ?

3. Il mondo delle “risonanze”

- Chicago, 1948. Entra in funzione il Ciclotrone di Chicago, puo’ produrre un faacio di pioni e studiare le reazioni dei pioni su p ed n
- 1951. Laura Fermi: *Enrico was as excited and pleased as a child who has received a new toy long dreamed of and exceeding expectations. He played with the cyclotron at all hours of the day and evening during that summer of 1951.*
- Fermi scopre la prima “risonanza”: uno stato π-N di spin 3/2, in 4 stati di carica, oggi indicato con la lettera Δ
  - $\Delta^- \rightarrow \pi^- n$; $\Delta^0 \rightarrow \pi^0 n, \pi^- p$; $\Delta^+ \rightarrow \pi^+ n, \pi^0 p$; $\Delta^{++} \rightarrow \pi^+ p$

The explosion of particle discoveries was so great, Fermi famously said,
“If I could remember the names of all these particles, I'd be a botanist.”

- con l’entrata in funzione di macchine giganti (Cosmotron, Bevatron) nelgi anni ’50 e l’uso di nuovi strumenti quali la camera a bolle, Luis Alvarez e il suo gruppo scoprono decine di risonanze, che si disintegrano rapidamente in mesoni e barioni.
- oggi conosciamo centinaio di risonanze, ogni anno si pubblica un libro con la lista aggiornata acura del Particle Data Group basato a Berkeley http://pdg.lbl.gov

ordine dal caos: una prima regolarita’

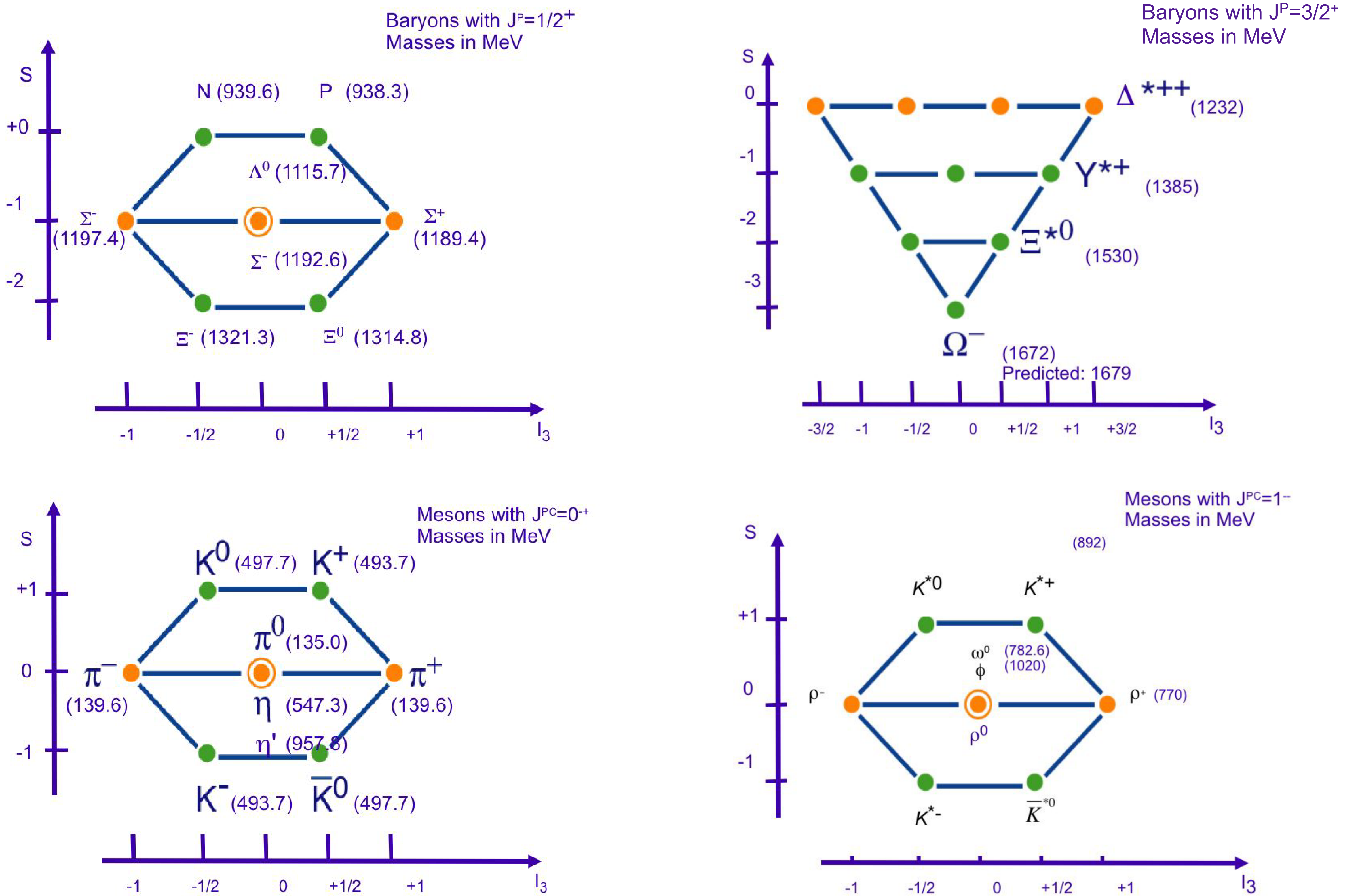
- Le masse di protone e neutrone sono molto prossime tra loro (infatti, ricordate?, i valori di A= peso atomico in unita’ di m_p sono circa interi)
- Heisenberg ipotizzo’ che ci fosse una simmetria per trasformazioni continue che “mescolano” p ed n (i simboli indicano i ***campi*** p ed n)

$$\begin{pmatrix} p \\ n \end{pmatrix} \rightarrow U \begin{pmatrix} p \\ n \end{pmatrix} = \begin{pmatrix} \alpha p + \beta n \\ \gamma p + \delta n \end{pmatrix}$$

- E’ un gruppo di trasformazioni che i matematici chiamano SU(2) (a indicare che U sono matrici 2x2, sono Unitarie e Speciali, ovvero con determinante =1)
- formalmente, queste trasformazioni sono le stesse sotto cui si trasformano i campi di spin 1/2 sotto rotazioni dello spazio 3dimensionale.
- i fisici indicano la simmetria SU(2) tra protone e neutrone col nome di ***spin isotopico*** (in breve ***isospin***)
- (il nome e’ alquanto improprio: il neutrone e’ collegato agli isotopi dei nuclei - stesso Z, diverso A- ma scambiando p ed n, Z cambia e A resta lo stesso!)
- se SU(2) e’ una simmetria delle interazioni forti, tutti i mesoni e i barioni si devono presentare in “multipletti” con masse molto vicine e cariche elettriche che variano a passi di 1
- la molteplicita’ e’ 2I+1, se I e’ l’ isospin totale (nucleone: I=1/2, 2I+1=2)
  - ci sono tre tipi di pioni: π^-, π^0, π^+ (I=1)
  - e quattro tipi di Δ: Δ^-, Δ^0, Δ^+, Δ^{++} (I=3/2)

Le risonanze piu' leggere

- da notare i multipletti di isospin completi,
- la stranezza, S, fornisce' la seconda dimensione
- $Q=I_3+1/2(B+S)$ (formale di Gell-Mann e Nishijima



4. Nuclear Democracy

- in the presence of very strong interactions (unitarity saturated) there is no clear distinction between composites and constituents:

$$\pi^{+} = p\bar{n} \;\rightarrow\; ?? \;\rightarrow\; n = \bar{p}\pi^{+}$$

which is which?

- in the sixties, for this reason, ***nuclear democracy*** (G. Chew and S. Frautschi) was considered to be the most promising approach;

XVI. ARE ALL STRONGLY INTERACTING PARTICLES COMPOSITE?

In the usual picture of atomic or nuclear physics, a very large number of composite atoms and nuclei are made up of electrons, neutrons, and protons. The electron, neutron, and proton are treated as elementary because most phenomena involve energies too low to excite their internal structure. In high-energy physics, on the other hand, the range of energies easily allows excitation and breakup of any particle. This circumstance motivated Chew and Frautschi[72)] to conjecture that they should all be treated on the same basis.

there is hope that their coupling constants and mass ratios can be determined from unitarity and maximal analyticity requirements. The way towards fulfilling this hope is believed to lie in the further development of the self-consistent or "bootstrap" method of calculation which was described in Chapter 7.

The constituent way, first attempts

- Fermi&Yang: only F=(p, n) are elementary,

$$mesons = F\bar{F}$$

- Sakata: one new constituent to account for strange particles: S= (p, n, Λ),

$$mesons = S\bar{S};\ baryons = SS\bar{S}$$

- one clear predictions: there must exist baryons with strangeness S=+1. ***Unfortunately it is a wrong prediction, no such particle seen until today*** !
- basic symmetry of Sakata model: SU(2)= isotopic spin symmetry ⇒ SU(3), unitary transformation of the Sakata triplet

- field theory paradigm was at its low, confined to QED, weak and gravitational interactions
- Murray Gell-Mann, when he found the way out, had to justify himself for using currents and Hamiltonian for the strong interactions,

216 From: *Phys Rev*, **125**, 1067–1084 (1962)

Symmetries of Baryons and Mesons*

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(Received March 27, 1961; revised manuscript received September 20, 1961)

standard field theory, where the Lagrangian density L of the strong interactions is expressed as a simple function of a certain number of local fields $\psi(x)$, which are supposed to correspond to the "elementary" baryons and mesons. Recently this type of formalism has come under criticism[3]; it is argued that perhaps none of the strongly interacting particles is specially distinguished as "elementary," that the strong interactions can be adequately described by the analyticity properties of the S matrix, and that the apparatus of field theory may be a misleading encumbrance.

Even if the criticism is justified, the field operators $j_\alpha(x)$, $\theta_{\alpha\beta}(x)$, and $J_\alpha(x)$ may still be well defined (by all their matrix elements, including analytic continuations thereof) and measurable in principle by interactions with external electromagnetic or gravitational fields or with lepton pairs. Since the Hamiltonian density H is a component of $\theta_{\alpha\beta}$, it can be a physically sensible quantity.

Finally....

Nowhere does our work conflict with the program of Chew *et al.* of dynamical calculation of the S matrix for strong interactions, using dispersion relations. If something like the Sakata model is correct, then most of the mesons are dynamical bound states or resonances, and their properties are calculable according to the program. Those particles for which there are fundamental fields (like n, p, Λ, and B^0 in the specific field-theoretic model) would presumably occur as CDD poles or resonances in the dispersion relations.[39]

quarks and gluons, to come!!

Nuclear Democracy(cont'd)

- Nuclear Democray and bootstrap had no real, recognized success,
- but it inspired the string theory of Gabriele Veneziano, which at present is the basis of many theories of Quantum Gravity
- maybe both Gell-Mann and Chew were right!
- For nuclear particles, the meaning of constituents was understood only in 1973:
- Nuclear democracy holds: all subnuclear particles are on the same level, they are all composite...
- ... quarks and gluons are elementary and the ***fundamental strong interactions become weak at short distance*** (D. Gross & F. Wilczek, D. Politzer)
- Well inside the proton, constituents mantain their personality.

6. SIMMETRIE IMPERFETTE

συμ, 'con', μετροσ, 'misura'

- Nel linguaggio di ogni giorno, simmetria implica proporzioni ben bilanciate. Gli oggetti simmetrici hanno grazia e bellezza.
- In matematica, la simmetria ha un significato più preciso. La simmetria di un oggetto è definita dalle trasformazioni che lasciano immutate le proporzioni delle sue differenti parti.
- Scambiare destra e sinistra, come in un normale specchio, è una operazione di simmetria (parità). Un oggetto simmetrico per parità apparirà immutato nello specchio.
- Simmetria implica ***predicibilità*** : possiamo prevedere la parte nascosta di un oggetto se ne conosciamo la simmetria, o l' esistenza di nuove particelle se conosciamo la simmetria che le collega alle particelle conosciute

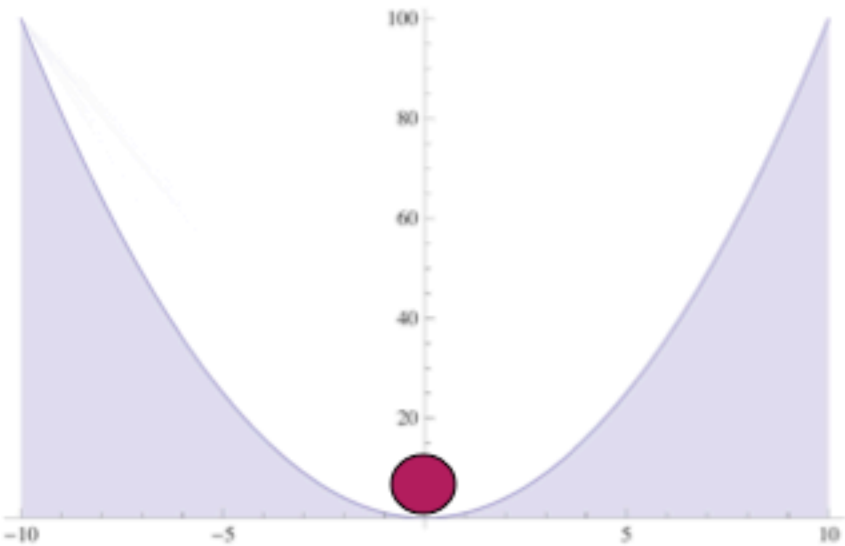
Non sappiamo perche' la simmetria sia un concetto utile in fisica, ma la predicibilita' e' stata la chiave del suo successo.

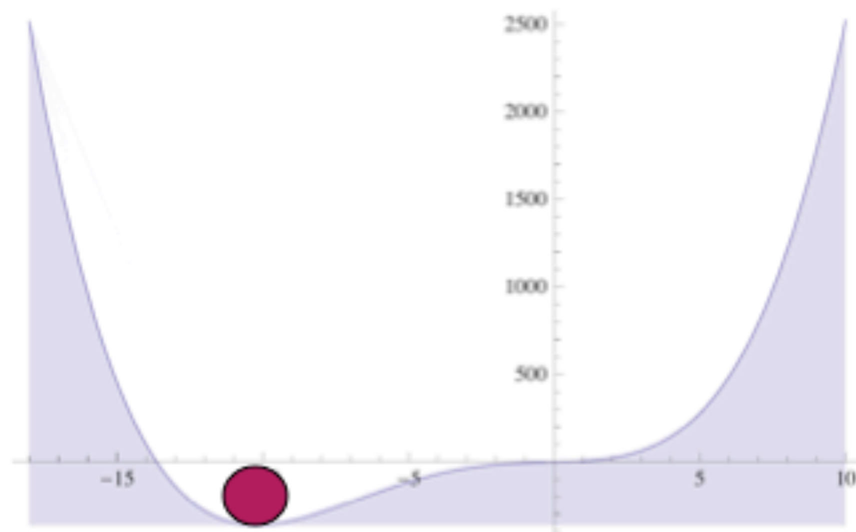
Simmetria= Capacità predittiva

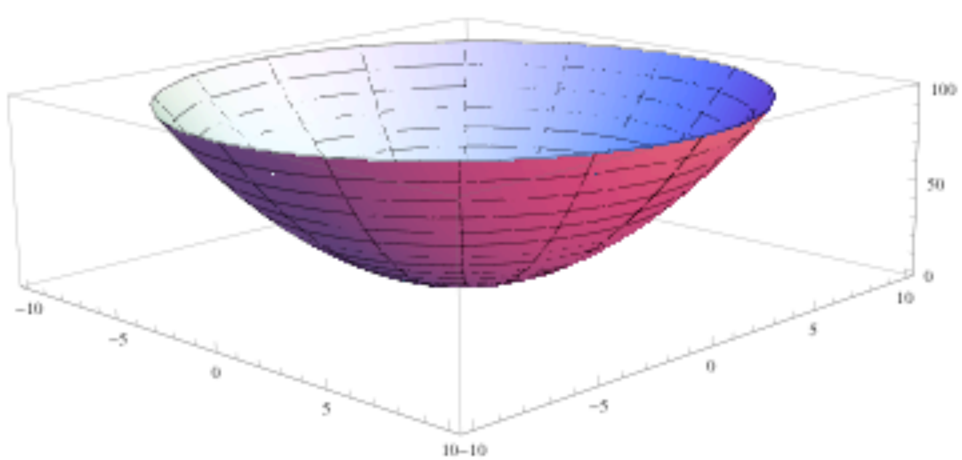
… nel vero quadro, la simmetria è splendidamente imperfetta

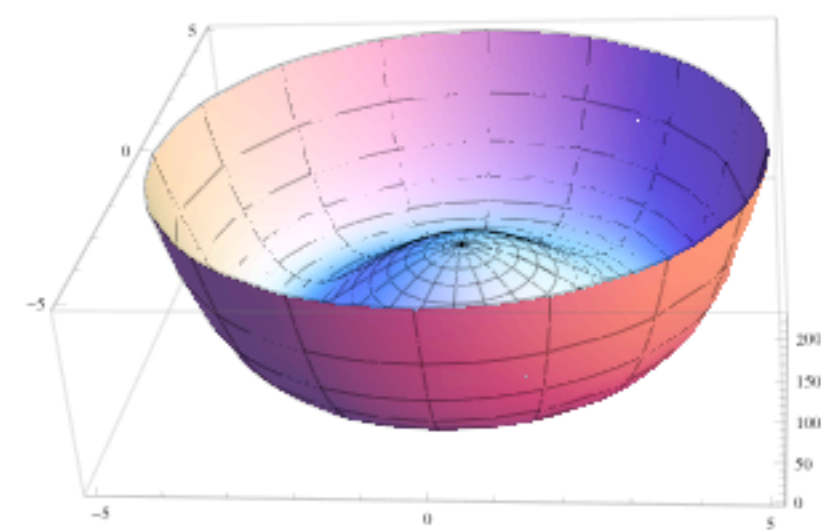
Piero della Francesca: Polittico della Misericordia

simmetria, rottura della simmetria... e rottura spontanea









Prossimamente qui !!!