Luciano Maiani:

Lezione Fermi 12

La teoria delle forze deboli dopo Fermi. Nicola Cabibbo ristabilisce l'universalità. Sogni di unificazione.

Sommario

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2. Current x current theory and the decays of Strange Particles
3. Enters Cabibbo
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1. Beta decays and Universality

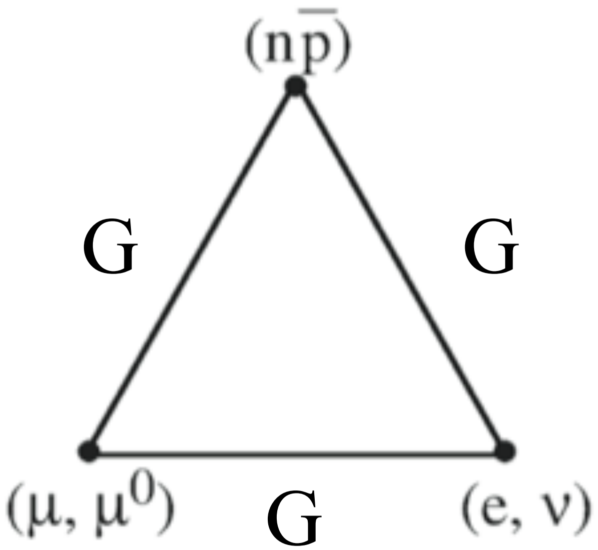
Neutron beta decay (E. Fermi, 1932)

$$N \to P + e + \bar{\nu}$$

Muon beta decay (B. Pontecorvo, 1947, G. Puppi, 1948)

$$\mu \to \nu_\mu + e + \bar{\nu}_e$$

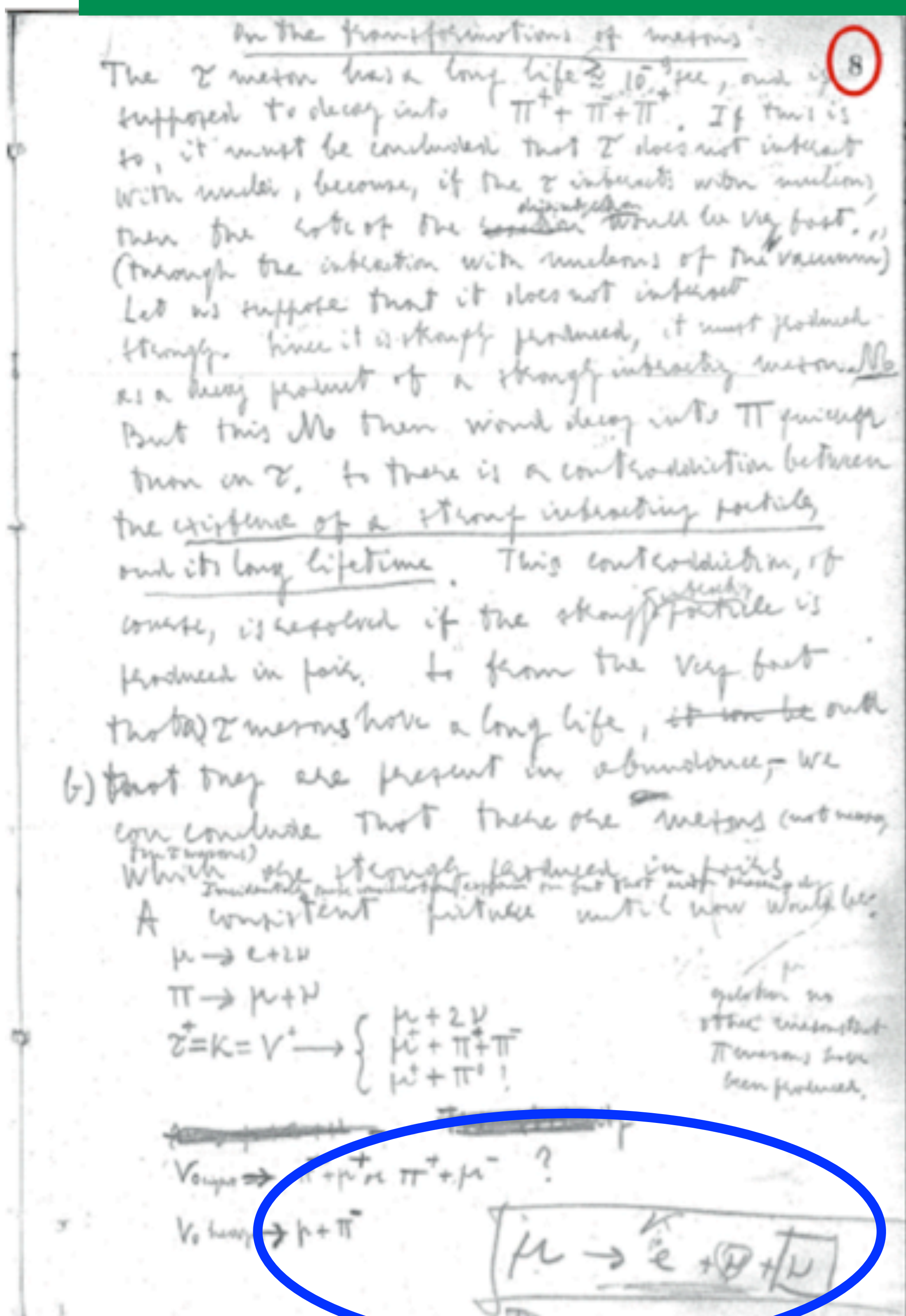
Puppi's triangle: the 3 basic processes have the same coupling. Maybe, the neutral particle coupled to muon is not the electron's neutrino



.. but Λ beta decay: $\Lambda \to p + e + \bar{\nu}_e$ has a coupling $G_\Lambda \sim 1/4\ G$

The multifaceted life of Pontecorvo

Pontecorvo's LogBook of 1950 and his memories of 1982



A symposium in Rome celebrated the centenary of Bruno Pontecorvo. **Luciano Maiani** was one of the speakers.

Bruno Pontecorvo (1913–1993) was born in Pisa but his scientific life began in Rome, when he was accepted into the group of physicists working at Sapenza University of Roma with Enrico Fermi. It was a small but exceptional group of young people attracted by the strong personality of Fermi, who were later known as "the boys of Via Panisperna" from the name of the street where the physics institute was located at that time. Pontecorvo arrived in Rome in time to participate in the discovery of radioactivity induced by slow neutrons, for which Fermi was to receive the Nobel Prize in Physics in 1938. A famous picture shows the group at the time of the discovery, with the notable absence of Bruno (figure 1). This was for good reason – he was behind the camera, taking the picture.

"I have to come back a long way (1947–1950). Several groups, among which J Steinberger, E Hincks and I, and others were investigating the (cosmic) muon decay. The result of the investigations was that the decaying muon emits 3 particles: one electron…and two neutral particles, which were called by various people in different ways: two neutrinos, neutrino and neutretto, ν and ν′, etc. I am saying this to make clear that for people working with muons in the old times, the question about different types of neutrinos has always been present…for people like Bernardini, Steinberger, Hincks and me…the two neutrino question was never forgotten."

Universal Weak Interactions

- In a 1961 book, Richard Feynman vividly described his and Murray Gell-Mann's satisfaction at explaining the close equality of the muon's and neutron's beta decay Fermi constants.
- They (and, independently, Gershtein & Zeldovich) had discovered the ***universality*** of the weak interactions, closely similar to the universality of the electric charge and a tantalising hint of a common origin of the two interactions.
- But Feynman recorded also his disconcert following the discovery that the Fermi constants of the strange particles, e.g. the Λ beta decay constant, turned out to be smaller by a factor of 4-5.
- It was up to Nicola Cabibbo to reconcile strange particle decays with the universality of weak interactions, paving the way to modern electroweak unification.

2. Current x Current theory and the Strange Particle decay puzzle (from R. P. Feynman, Theory of Fundamental Processes)

natural from one assumption. That is that the Fermi couplings are of the nature of the interaction of a kind of current with itself:

$$J \longleftrightarrow J \qquad \text{Action} \approx J \times J^* \qquad (12\text{-}4)$$

and the problem is to find the composition of the current J, the sum of several parts. The couplings (6-4), (6-5), and (6-6) described previously result if J is written

$e \rightarrow \nu \quad \mu \rightarrow \nu \quad n \rightarrow p \quad \Lambda \rightarrow p$?

$$J = (\bar{\nu}e) + (\bar{\nu}\mu) + (\bar{p}n) + X \qquad (12\text{-}5)$$

Experimentally the coefficient of all first three terms are equal. All our three new couplings will result if we add to J just one term, say X, which changes strangeness. Above we have suggested solely as an example what X might be but we shall now have to consider more seriously what properties the term X might have.

An immediate consequence of this idea is that the coefficients of X to each of the three currents $(\bar{\nu}e)$, $(\bar{\nu}\mu)$, and $(\bar{p}n)$ are equal. That is, the couplings (12-1), (12-2), and (12-3) must all have the same coefficient [although it need not equal the coefficient of (6-4), (6-5), and (6-6)].

electron-muon universality well obeyed in Strange Particle decays

Gell-Mann and Levy

- An observation made in a 1960 by M. Gell-Mann and M. Levy is often quoted as a precursor or at least a source of inspiration for Cabibbo. This is justified to some extent, but the role of Gell-Mann and Levy's observation needs not to be overestimated. For one, the Gell-Mann and Levy's paper was well known to all those working in the field (and quoted by Cabibbo).

- In G-M & L paper, the weak current is written in the Sakata model, with elementary P, N and Λ. All hadrons are supposed to be made by these three fundamental fields.
- G-M & L observe that one could relate the reduction of the Λ vs the muon coupling by assuming the following form of the weak vector current:

$$V_\lambda = \frac{1}{\sqrt{1-\epsilon^2}}\left[\bar{P}\gamma_\lambda\left(N+\epsilon\Lambda\right)\right]$$

But:

- ***nobody knew how to proceed from the G-M&L formula*** to a real calculation of meson and baryon decays, for two reasons:

• The Sakata model was already known to be substantially wrong, due to the absence of the positive-strangeness hadrons. Thus the inclusion of the decays of the S=-1 and S=-2 hyperons was completely out of reach.

• The important point of the non-renormalisation was missed. In Gell-Mann and Levy's words: *There is, of course, a renormalization factor for that decay*, (i.e. Λ decay) *so we cannot be sure that the low rate really fits in with such a picture*.

SU(3) Symmetry and weak interactions

Gatto & Cabibbo (1961) and others observed that the octet currents associated to the newly discovered SU(3) symmetry include a *strangeness changing current* that could be associated with strangeness changing decays, in addition to the *isospin current* responsible for strangeness-non-changing beta decays (CVC).

The identification, however, implied the rule ΔS= ΔQ in the decays, in conflict with some experimental evidence: there was a single event $\Sigma^+ \rightarrow \mu^+ + n + \nu$ reported in an emulsion experiment, *A. Barbaro Gualtieri et al.*, (PRL 1962).

In addition, the problem remained how to formulate correctly the concept of CVC and muon-hadron universality in the presence of the three currents:

$$V_\lambda^{lept} = \bar{\nu}_\mu \gamma_\lambda \mu + \bar{\nu}_e \gamma_\lambda e \ (\Delta \mathrm{Q} = 1); \quad \boldsymbol{e \rightarrow \nu_e \ \ \mu \rightarrow \nu_\mu}$$

$$V_\lambda^{(1)} + i V_\lambda^{(2)} \ (\Delta \mathrm{S} = 0, \ \Delta \mathrm{Q} = 1) \quad \boldsymbol{n \rightarrow p, ...}$$

$$V_\lambda^{(5)} + i V_\lambda^{(6)} \ (\Delta \mathrm{S} = \Delta \mathrm{Q} = 1) \quad \boldsymbol{\Lambda \rightarrow p, ...}$$

3. Enters Cabibbo

- laurea in 1958, tutor Bruno Touschek
- first thoretical physicist in Frascati, hired by G. Salvini
- meets there Raoul Gatto (5 years elder) who was coming back from Berkeley
- exciting times in Frascati: $e^+ e^-$ collider AdA, later Adone, new particles (the eta meson), SU(3), etc.
- Cabibbo & Gatto author an important aricle on $e^+ e^-$ physics (the Bible)
- together investigate the weak interactions of hadrons in the light of the new SU(3) symmetry

Only one hadronic current!

- In his 1963 paper, Nicola made a few decisive steps.
- he decided to ignore the evidence for a ΔS= -ΔQ component (Nicola was a good friend of Paolo Franzini, who had a larger statistics of hyperon decays with no event like Galtieriet al.);
- he formulated a notion of universality between each *leptonic current* and *one, and only one hadronic current*, a combination of the SU(3) currents with ΔS=0 and ΔS=1: the hadronic current has to be *equally normalized* to the lepton current. Axial currents are inserted via the V-A hypothesis.

$$V_\lambda^{(hadron)} = a\left[V_\lambda^{(1)} + iV_\lambda^{(2)}\right] + b\left[V_\lambda^{(5)} + iV_\lambda^{(6)}\right]$$

$$a^2 + b^2 = 1$$

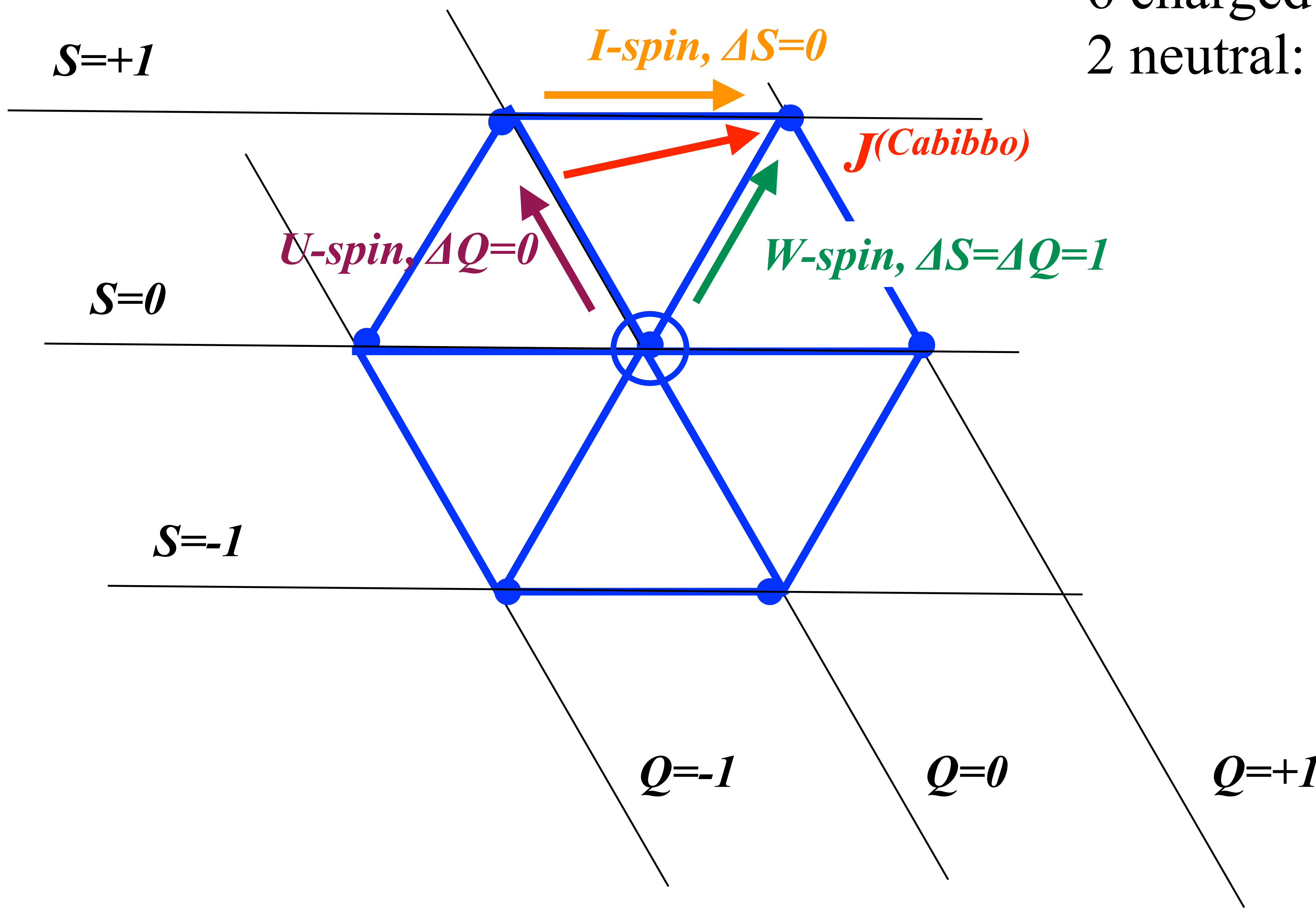
$$J_\lambda^{lept} = \bar{\nu}_\mu \gamma_\lambda (1-\gamma_5)\mu + \bar{\nu}_e \gamma_\lambda (1-\gamma_5) e;$$

$$J_\lambda^{(hadron)} = \cos\theta\left[J_\lambda^{(1)} + iJ_\lambda^{(2)}\right] + \sin\theta\left[J_\lambda^{(5)} + iJ_\lambda^{(6)}\right];$$

$$J_\lambda^{(i)} = V_\lambda^{(i)} - A_\lambda^{(i)}$$

The angle θ is a new constant of Nature, since known as *the Cabibbo angle*.

Generators in SU(3) octet space

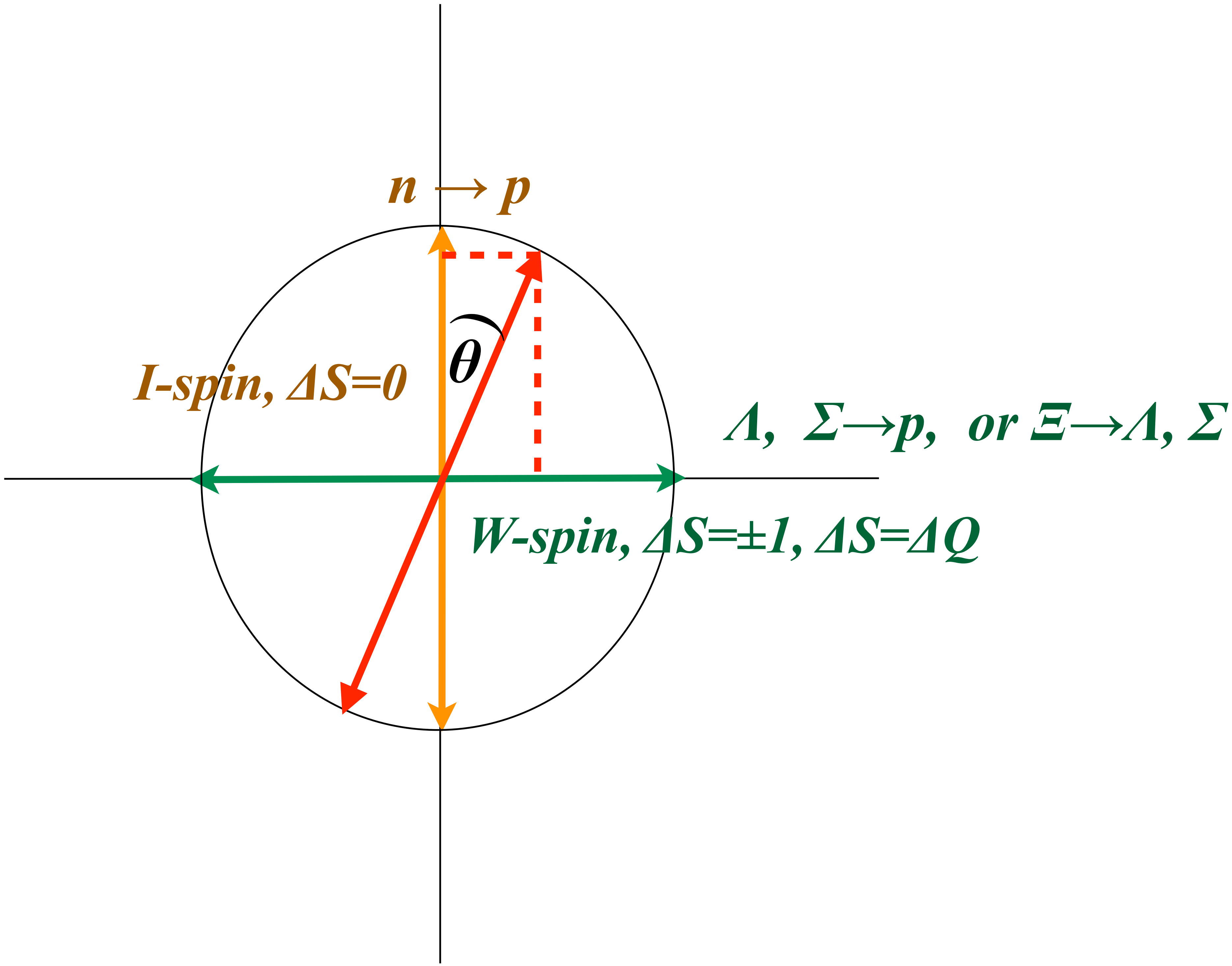


8 SU(3) Generators:
6 charged: $I^{\pm}$, $W^{\pm}$, $U^{\pm}$,
2 neutral: I_3, I_8

$$\mathbf{J}^{(Cabibbo)} = \cos\theta(\mathbf{I}^{+}) + \sin\theta(\mathbf{W}^{+})$$

Nicola used to say that he was motivated by the analogy with the propagation of polarized light in a polarimeter

Light polarized at angle θ sent through orthogonal polarimeters is transmitted with Probability = $\cos^2\theta$ (vertical: ***n → p***) or $\sin^2\theta$ (horizontal: ***Λ, Σ→ p, Ξ→Λ, Σ***)



Currents belong to SU(3)xSU(3)
Partial conservation of the vector and axial vector currents protects the normalization of strenght
Gatto-Ademollo theorem: vector current is non renormalized to first order in SU(3) breaking

The phenomenological success of the Cabibbo theory has been but reinforced by the most recent data from Frascati, FermiLab and CERN.

equal normalization ?

- It was clarified by Cabibbo himself, in his 1994 Erice lectures, that the weak angle specifies the direction in SU(3) octet space of a weak isospin group with respect to the direction identified by the medium-strong interactions, which are responsible for the breaking of the symmetry itself. In the absence of symmetry breaking, one could identify the weak isospin group with the isospin symmetry and the strange particles would be stable under weak decays.
- The interplay of the weak and medium-strong interactions to determine the value of θ is far-reaching. It has remained in the present unified theory in the form of a *misalignment between the weak isospin subgroup of the flavor symmetry and the quark mass matrix*, which arises from the spontaneous symmetry breaking of the weak isospin.

4. Cabibbo Theory with quarks

- The Gell-Mann-Levy formula *was given a new life* after the consolidation of the Cabibbo theory, *in the context of the quark model*. If quarks and flavor-singlet gluons are the fundamental particles, as we know today, beta decays of baryons simply reflect the two transitions

$$d \rightarrow u, \quad s \rightarrow u$$

- (this is similar to Fermi's idea that beta decays of nuclei are simply the manifestation of the $n \rightarrow p$ transition)
- in the quark picture, the Cabibbo weak current takes the simple form:

$$J_\lambda = \cos\theta \left[\bar{u}\gamma_\lambda(1-\gamma_5)\left(d + \tan\theta s\right)\right] =$$
$$= \bar{u}\gamma_\lambda(1-\gamma_5)d_C$$

Comparison of the BNL (blue) and Frascati (red) results with the PFDG 02 values (black) and with the prediction of Cabibbo Theory and unitarity (yellow band). The latest results look quite consistent with unitarity.

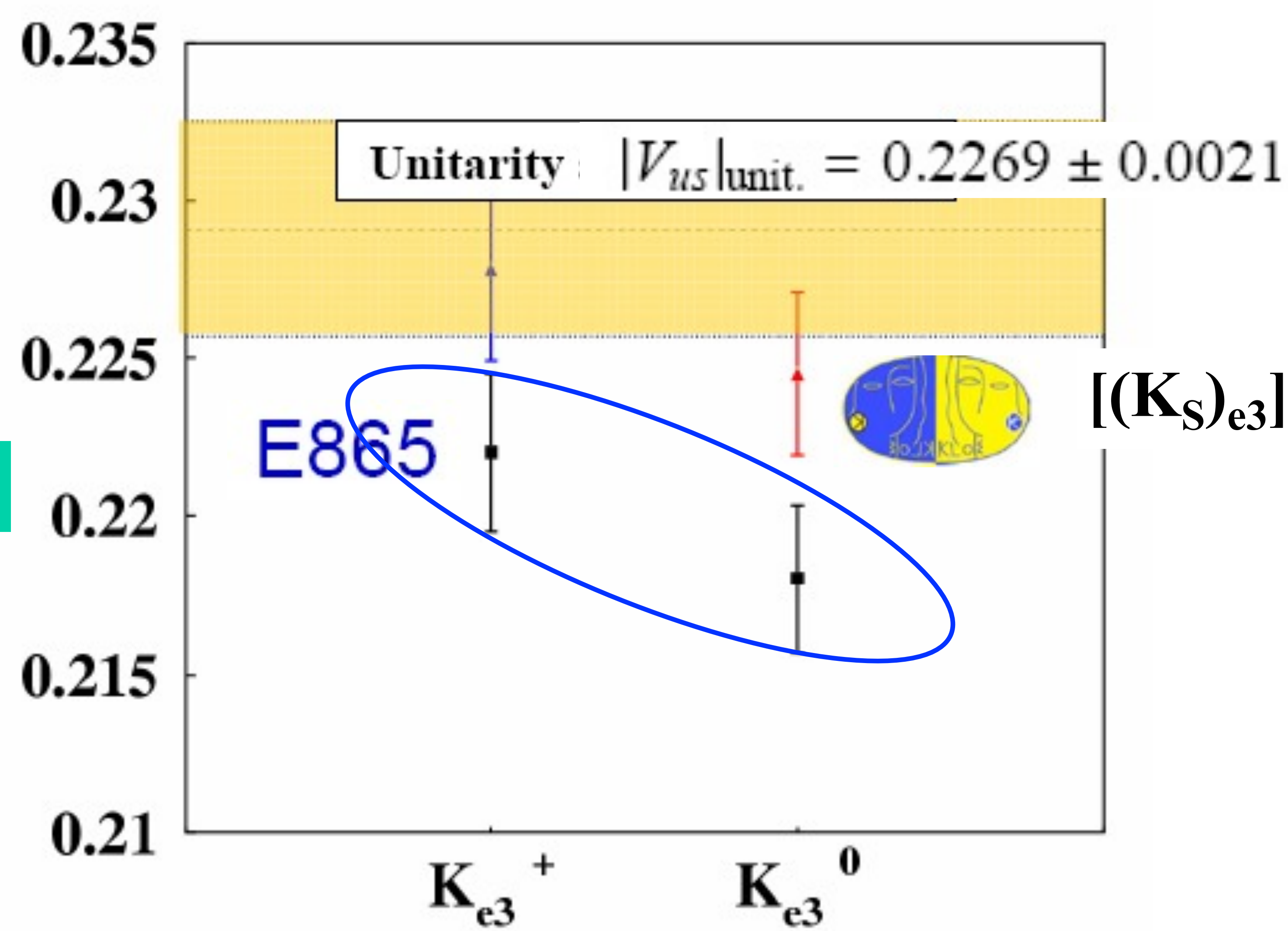
$K_S \to \pi e \nu$ decay: V_{us} determination

PDG02, CKMwg use

$$f_+^{K^0\pi^-}(0) = 0.961 \pm 0.008$$

From **Leutwyler, Roos**
Z.Phys. C 25 1984

- p^4 contr. in χPT



Hyperon decays: NA48 data!

N. Cabibbo, E. C. Swallow and R. Winston, hep-ph/0307214, hep-ph/0307298.

$$|V_{us}|_{Hyp} = 0.2250 \pm 0.0027_{exp}$$

New!!! KTeV ($K_L l3$):

$$|V_{us}| = 0.2252 \pm 0.0008_{KTeV} \pm 0.0021_{ext}$$

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Closing up on Cabibbo-theory

From its publication, the Cabibbo theory has been seen as a crucial development:

- indicating the correct way to embody lepton-hadron universality
- enjoying a heartening phenomenological success, which indicated that we could be on the right track towards the fundamental theory of the weak interactions.

The authoritative book by A. Pais, (*Inward Bound*), in its chronology, quotes the Cabibbo theory among the most important developments in post-war Particle Physics.

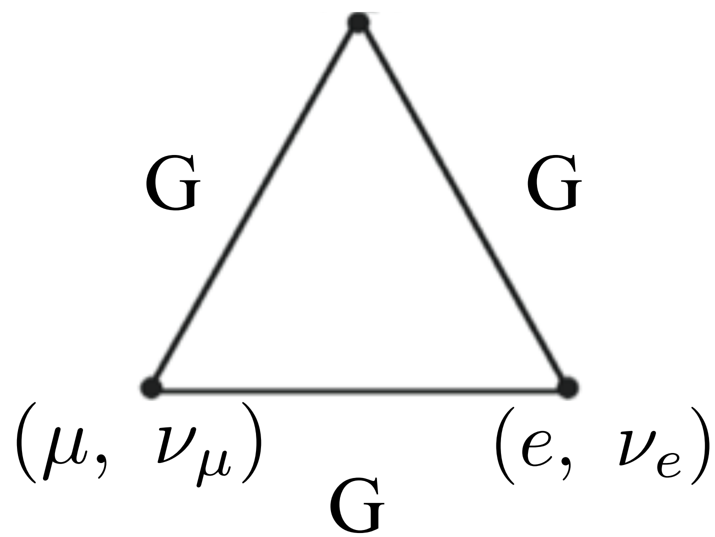
•John Iliopoulos, in *Gauge Theories* (Roma, 2010):"*There are very few articles in the scientific literature in which one does not feel the need to change a single word and Cabibbo's is definitely one of them. With this work he established himself as one of the leading theorists in the domain of weak interactions*".

Dirac Medallists 2010

The 2010 Dirac medal has been awarded by ICTP to Nicola Cabibbo and Ennackal Sudarshan " for their fundamental contributions to the understanding of weak interactions

5. Puppi-Cabibbo Triangle and dreams of Unification

$(d_C = \cos\theta \; d + \sin\theta \; s)$



- Cabibbo theory is the basis to construct a field theory replacing Fermi theory;
- J. Schwinger had suggested that QED could be unified with Weak Interactions, if mediated by the Intermediate Vector Boson (charged);
- in 1961Sheldon Lee Glashow proposed a theory of the electron and neutrino weak and electromagnetic interactions unifying e.m. and weak interactions
- and discovered that a neutral Vector Boson was needed, in addition to the photon...
- and that particle masses could not respect the symmetry of the theory...
- ...and quark weak interactions could not be fitted in !!

...is Unification the right answer?