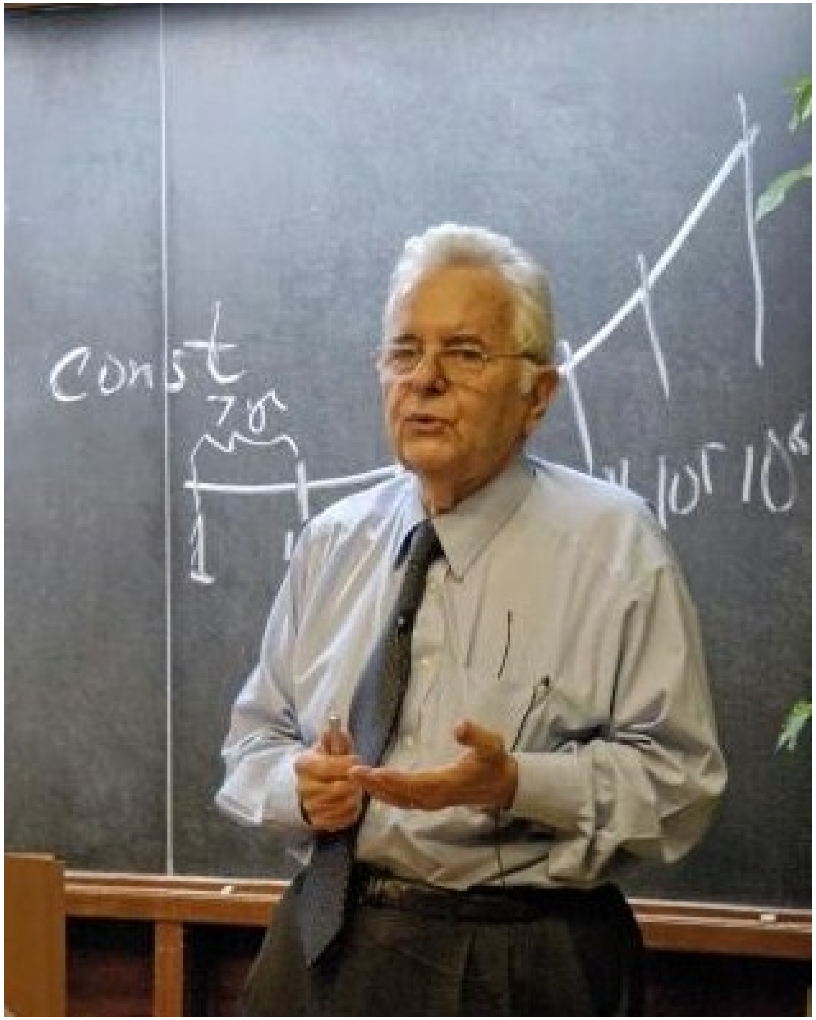
Nicola Cabibbo:

his scientific legacy and some personal recollections

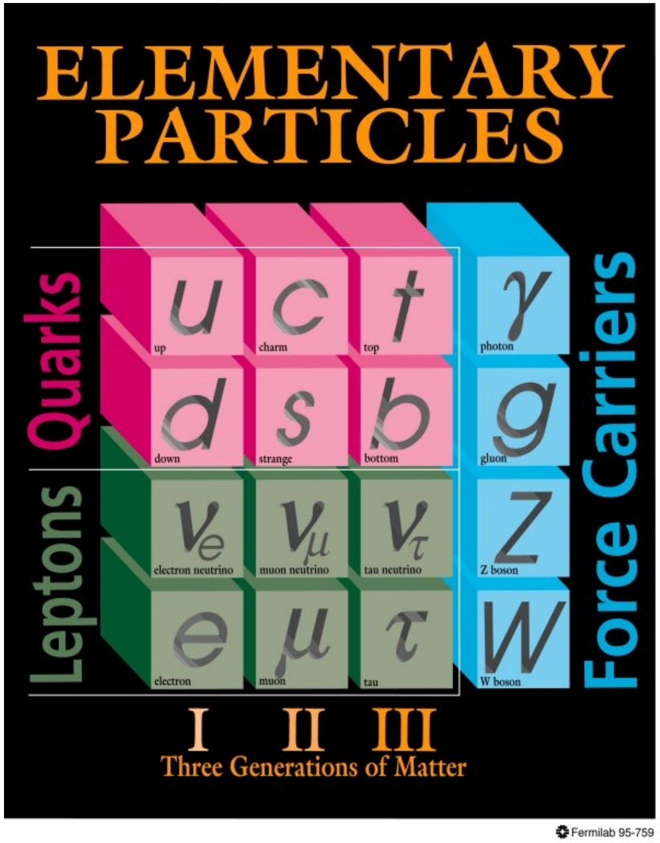


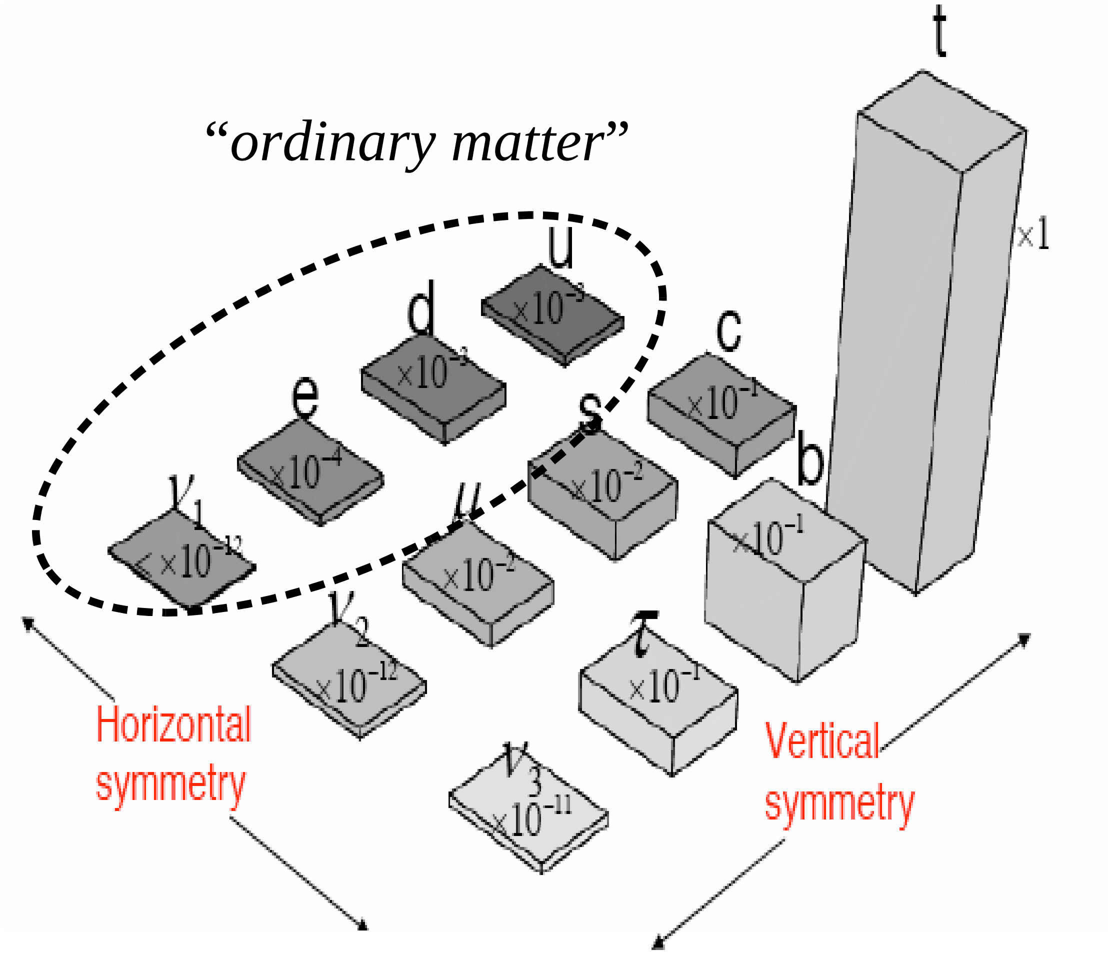
Nicola Cabibbo:
his scientific legacy and some personal recollections

- Flavour physics today
- Birth and rise of “CKM” physics
- Beside CKM...
- What I learned from him

Flavour physics today

The mystery of why we have 3 generations of quarks and leptons and what distinguish them, is one of the most fascinating and, to a large extent, still open problems in particle physics





Cabibbo contribution to this field in the early '60 is one of the pillars of our present understanding of particle physics

Flavour physics today

Within the Standard Model quark masses and flavour mixing (what “distinguishes” the 3 families) originates from (*or better “is hidden in”*...) the Higgs sector:

$$\mathscr{L}_{\mathrm{SM}} = \mathscr{L}_{\mathrm{gauge}}(A_a, \psi_i) + \mathscr{L}_{\mathrm{Higgs}}(\phi, A_a, \psi_i)$$

- *Natural*
- Experimentally tested with high accuracy
- Stable with respect to quantum corrections
- Highly symmetric

- *Ad hoc*
- Necessary to describe data [*clear indication of a non-invariant vacuum*] but not tested in its dynamical form
- Not stable with respect to quantum corrections
- Origin of the flavour structure of the model

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{gauge}}(A_{\text{a}}, \psi_{\text{i}}) + \mathscr{L}_{\text{Higgs}}(\phi, A_{\text{a}}, \psi_{\text{i}})$$

3 identical replica of the basic fermion family

[$\psi = Q_L, u_R, d_R, L_L, e_R$] ⇒ huge flavour-degeneracy

$$\Sigma_{\psi = Q_L, u_R, d_R, L_L, e_R} \, \Sigma_{\text{i}=1..3} \, \bar{\psi}_{\text{i}} \not{D} \psi_{\text{i}}$$

The gauge Lagrangian is invariant under 5 independent U(3) global rotations for each of the 5 independent fermion fields

E.g.: $Q_L^{\,i} \to U^{ij} Q_L^{\,j}$

U(1) flavour-independent phase

×

SU(3) flavour-dependent mixing matrix

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\text{Higgs}}(\phi, A_a, \psi_i)$$

3 identical replica of the basic fermion family

$[\, \psi = Q_L , u_R, d_R, L_L, e_R \,]$ ⇒ huge flavour-degeneracy

Within the SM the flavour-degeneracy is broken only by the Yukawa interaction:

in the quark sector:

$$\left[\begin{aligned} &\bar{Q}_L^{\,i}\, Y_D^{ik}\, d_R^{\,k}\, \phi + h.c. \rightarrow \bar{d}_L^{\,i}\, M_D^{ik}\, d_R^{\,k} + \ldots \\ &\bar{Q}_L^{\,i}\, Y_U^{ik}\, u_R^{\,k}\, \phi_c + h.c. \rightarrow \bar{u}_L^{\,i}\, M_U^{ik}\, u_R^{\,k} + \ldots \end{aligned}\right.$$

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}}(A_a, \psi_i) + \mathcal{L}_{\mathrm{Higgs}}(\phi, A_a, \psi_i)$$

3 identical replica of the basic fermion family
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Within the SM the flavour-degeneracy is broken only by the Yukawa interaction:

in the quark sector:

$$\left[\begin{array}{l} \bar{Q}_L{}^i\, Y_D{}^{ik}\, d_R{}^k\, \phi \;+\; h.c. \;\longrightarrow\; \bar{d}_L{}^i\, M_D{}^{ik}\, d_R{}^k + \dots \\ \bar{Q}_L{}^i\, Y_U{}^{ik}\, u_R{}^k\, \phi_c \;+\; h.c. \;\longrightarrow\; \bar{u}_L{}^i\, M_U{}^{ik}\, u_R{}^k + \dots \end{array}\right.$$

The Y are not hermitian ⟶ diagonalised by bi-unitary transformations:

$$V_D{}^+\, Y_D\, U_D = \mathrm{diag}(y_b\,, y_s\,, y_d)$$

$$V_U{}^+\, Y_U\, U_U = \mathrm{diag}(y_t\,, y_c\,, y_u)$$

$$y_i = \frac{\sqrt{2}\,\mathrm{m}_{\mathrm{q_i}}}{\langle\phi\rangle} \approx \frac{\mathrm{m}_{\mathrm{q_i}}}{174\ \mathrm{GeV}}$$

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}}(A_{\mathrm{a}}, \psi_{\mathrm{i}}) + \mathcal{L}_{\mathrm{Higgs}}(\phi, A_{\mathrm{a}}, \psi_{\mathrm{i}})$$

3 identical replica of the basic fermion family

$[\ \psi = Q_L\,, u_R, d_R, L_L, e_R\ ]$ $\Rightarrow$ huge flavour-degeneracy

Within the SM the flavour-degeneracy is broken only by the Yukawa interaction:

in the quark sector:

$$\left[\begin{array}{l} \bar{Q}_L{}^i\, Y_D{}^{ik}\, d_R{}^k\, \phi \;+\; h.c. \;\rightarrow\; \bar{d}_L{}^i\, M_D{}^{ik}\, d_R{}^k + \ldots \\ \bar{Q}_L{}^i\, Y_U{}^{ik}\, u_R{}^k\, \phi_{\mathrm{c}} \;+\; h.c. \;\rightarrow\; \bar{u}_L{}^i\, M_U{}^{ik}\, u_R{}^k + \ldots \end{array}\right.$$

but the residual flavour symmetry let us to choose a (gauge-invariant) flavour basis where one of the two Yukawas is diagonal:

$$Y_D = \mathrm{diag}(y_d, y_s, y_b)$$
$$Y_U = \mathrm{V}^{+} \times \mathrm{diag}(y_u, y_c, y_t)$$

or

$$M_D = \mathrm{V} \times \mathrm{diag}(y_d, y_s, y_b)$$
$$M_U = \mathrm{diag}(y_u, y_c, y_t)$$

unitary matrix

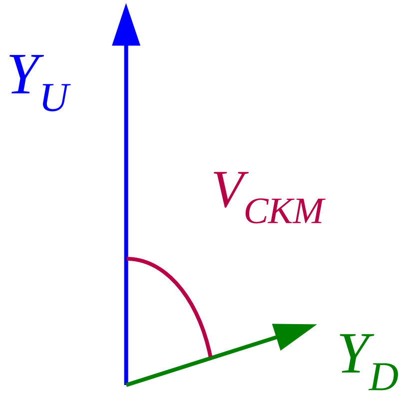
$$\bar{Q}_L^{\,i}\, Y_D^{ik}\, d_R^{\,k}\, \phi \;\rightarrow\; \bar{d}_L^{\,i}\, M_D^{ik}\, d_R^{\,k} + \ldots \qquad M_D = \mathrm{diag}(m_d, m_s, m_b)$$

$$\bar{Q}_L^{\,i}\, Y_U^{ik}\, u_R^{\,k}\, \phi_c \;\rightarrow\; \bar{u}_L^{\,i}\, M_U^{ik}\, u_R^{\,k} + \ldots \qquad M_U = V^{+} \times\, \mathrm{diag}(m_u, m_c, m_t)$$

To diagonalize also the second mass matrix we need to rotate separately u_L & d_L (non gauge-invariant basis) ⇒ V appears in charged-current gauge interactions:

$$J_W^{\mu} = \bar{u}_L\, \gamma^{\mu} d_L \;\rightarrow\; \bar{u}_L\, \underset{\uparrow}{V}\, \gamma^{\mu} d_L$$

Cabibbo-Kobayashi-Maskawa
(CKM) mixing matrix



N.B.: Don't forget that this non-trivial mixing originates only from the Higgs sector ($V_{ij} \rightarrow \delta_{ij}$ if we *switch-off* Yukawa interactions !)

$$\bar{Q}_L^{\,i}\, Y_D^{\,ik}\, d_R^{\,k}\, \phi \;\rightarrow\; \bar{d}_L^{\,i}\, M_D^{\,ik}\, d_R^{\,k} + \dots \qquad M_D = \mathrm{diag}(m_d, m_s, m_b)$$

$$\bar{Q}_L^{\,i}\, Y_U^{\,ik}\, u_R^{\,k}\, \phi_c \;\rightarrow\; \bar{u}_L^{\,i}\, M_U^{\,ik}\, u_R^{\,k} + \dots \qquad M_U = V^{+} \times \mathrm{diag}(m_u, m_c, m_t)$$

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Cabibbo-Kobayashi-Maskawa
(CKM) mixing matrix

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Eliminating the unobservable quark phases, we are left with:

- $N(N-1)/2$ ⇒ 3 real parameters (*flavour mixing*)
- $N(N+1)/2 - (2N-1) = (N-2)(N-1)/2$ ⇒ 1 complex phases (*CP violation*)

Birth and rise of CKM physics

All this seems “quite obvious” these days, but it was highly non-trivial 50 years ago, when there was no electroweak theory, no quark model, no charm...

When the “paricle physics zoo” was confined to a few light and strange hadrons.

I was not there at that time...

The best I can do to tell you this story is to use the slides that Nicola presented two years ago at the CKM 2008 conference.

Birth and Raise of CKM physics

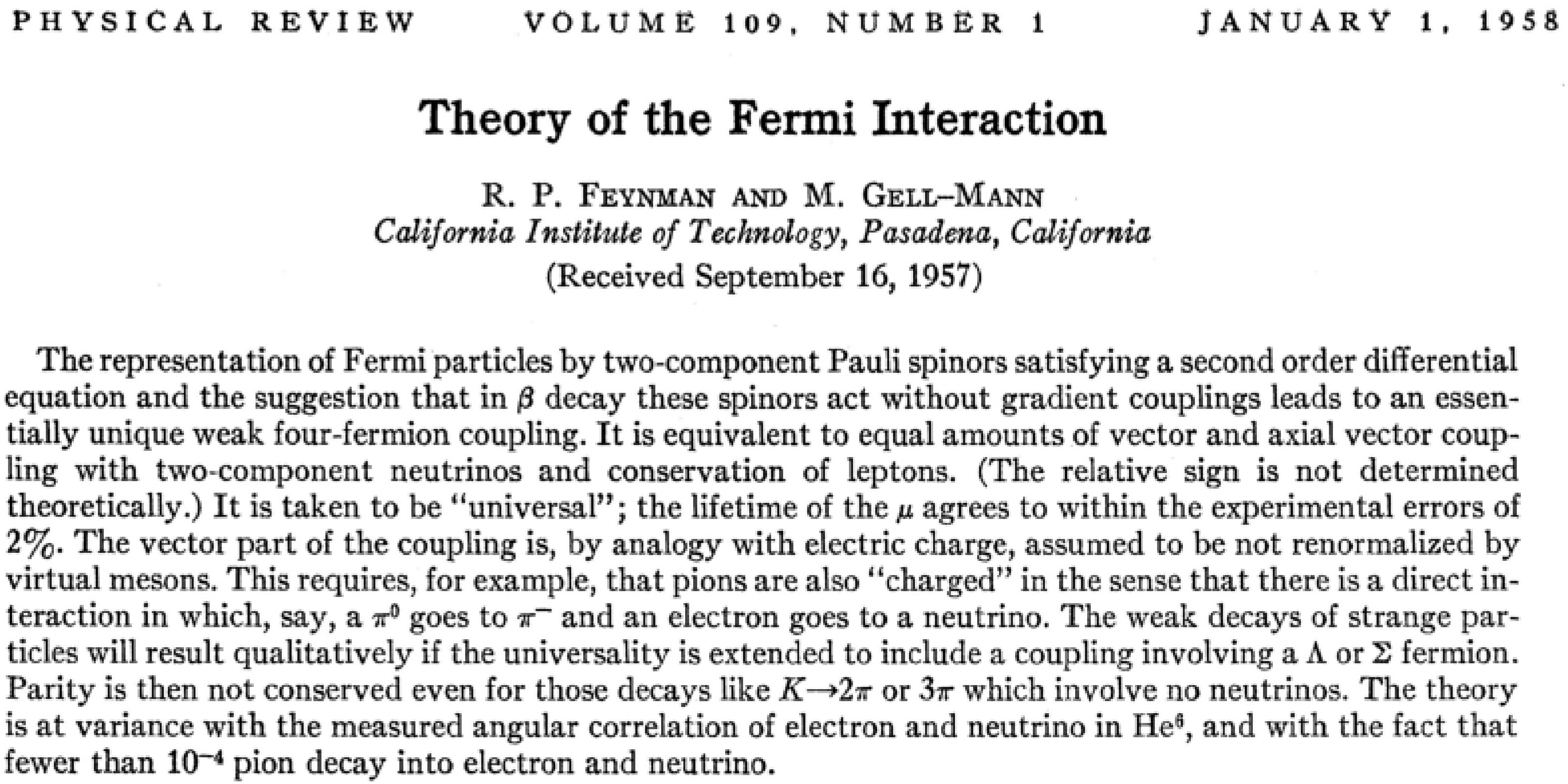
Nicola Cabibbo

Università di Roma "La Sapienza"
INFN — Sezione di Roma

9 Sept. 2008

The Need for Flavor Mixing — 1

The inspiration for flavor mixing first arose from the 1958 paper by Feynman and Gell-Mann on the V-A theory of weak interactions,



PHYSICAL REVIEW VOLUME 109, NUMBER 1 JANUARY 1, 1958

Theory of the Fermi Interaction

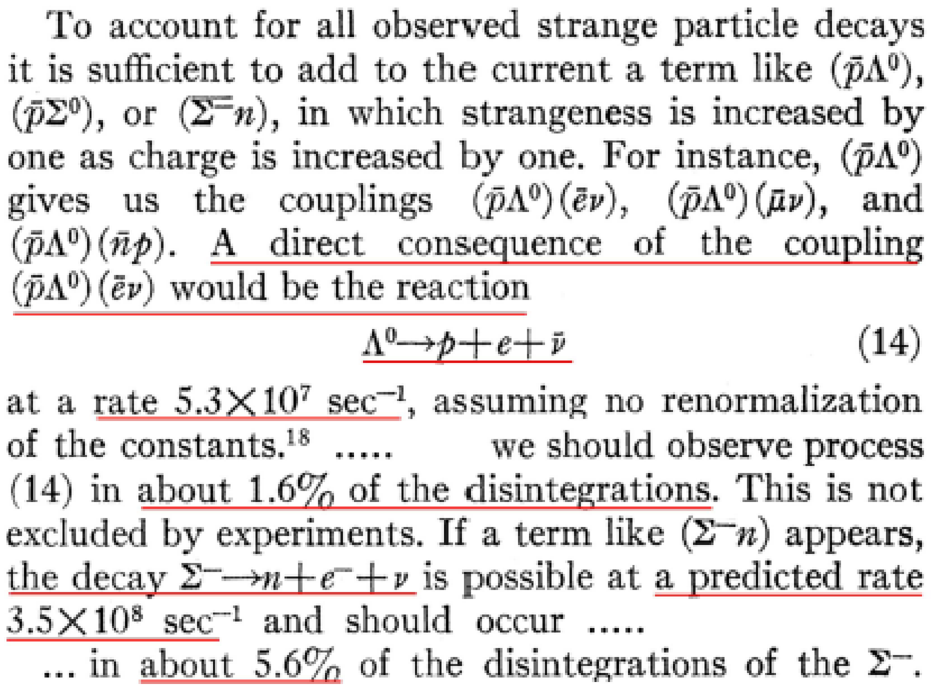
R. P. FEYNMAN AND M. GELL-MANN
California Institute of Technology, Pasadena, California

(Received September 16, 1957)

The representation of Fermi particles by two-component Pauli spinors satisfying a second order differential equation and the suggestion that in β decay these spinors act without gradient couplings leads to an essentially unique weak four-fermion coupling. It is equivalent to equal amounts of vector and axial vector coupling with two-component neutrinos and conservation of leptons. (The relative sign is not determined theoretically.) It is taken to be "universal"; the lifetime of the μ agrees to within the experimental errors of 2%. The vector part of the coupling is, by analogy with electric charge, assumed to be not renormalized by virtual mesons. This requires, for example, that pions are also "charged" in the sense that there is a direct interaction in which, say, a π^0 goes to π^- and an electron goes to a neutrino. The weak decays of strange particles will result qualitatively if the universality is extended to include a coupling involving a Λ or Σ fermion. Parity is then not conserved even for those decays like $K \to 2\pi$ or 3π which involve no neutrinos. The theory is at variance with the measured angular correlation of electron and neutrino in He^6, and with the fact that fewer than 10^{-4} pion decay into electron and neutrino.

The First Problem

From the Feynman — Gell-Mann paper...



To account for all observed strange particle decays it is sufficient to add to the current a term like $(\bar{p}\Lambda^0)$, $(\bar{p}\Sigma^0)$, or $(\overline{\Sigma^-}n)$, in which strangeness is increased by one as charge is increased by one. For instance, $(\bar{p}\Lambda^0)$ gives us the couplings $(\bar{p}\Lambda^0)(\bar{e}\nu)$, $(\bar{p}\Lambda^0)(\bar{\mu}\nu)$, and $(\bar{p}\Lambda^0)(\bar{n}p)$. A direct consequence of the coupling $(\bar{p}\Lambda^0)(\bar{e}\nu)$ would be the reaction

$$\Lambda^0\to p+e+\bar{\nu} \qquad (14)$$

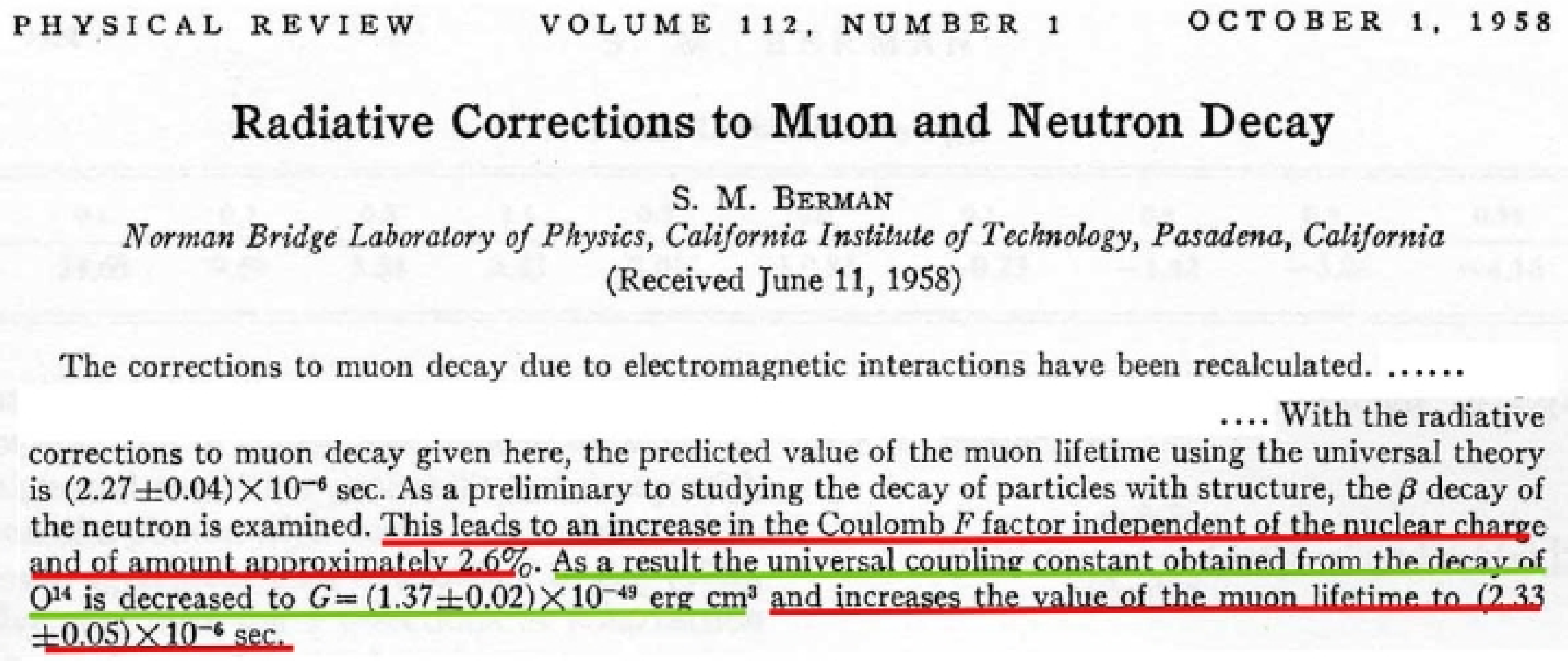
at a rate 5.3×10^7 sec^{-1}, assuming no renormalization of the constants.[18] ..... we should observe process (14) in about 1.6% of the disintegrations. This is not excluded by experiments. If a term like (Σ^-n) appears, the decay $\Sigma^-\to n+e^-+\nu$ is possible at a predicted rate 3.5×10^8 sec^{-1} and should occur .....

... in about 5.6% of the disintegrations of the Σ^-.

Around 1962 it became clear than these rates were ≈ 20 times smaller!

The Need for Flavor Mixing — 2

The second hint is due to by Sam Berman, Feynman's student, and appeared at the end of 1958.



PHYSICAL REVIEW VOLUME 112, NUMBER 1 OCTOBER 1, 1958

Radiative Corrections to Muon and Neutron Decay

S. M. Berman
Norman Bridge Laboratory of Physics, California Institute of Technology, Pasadena, California

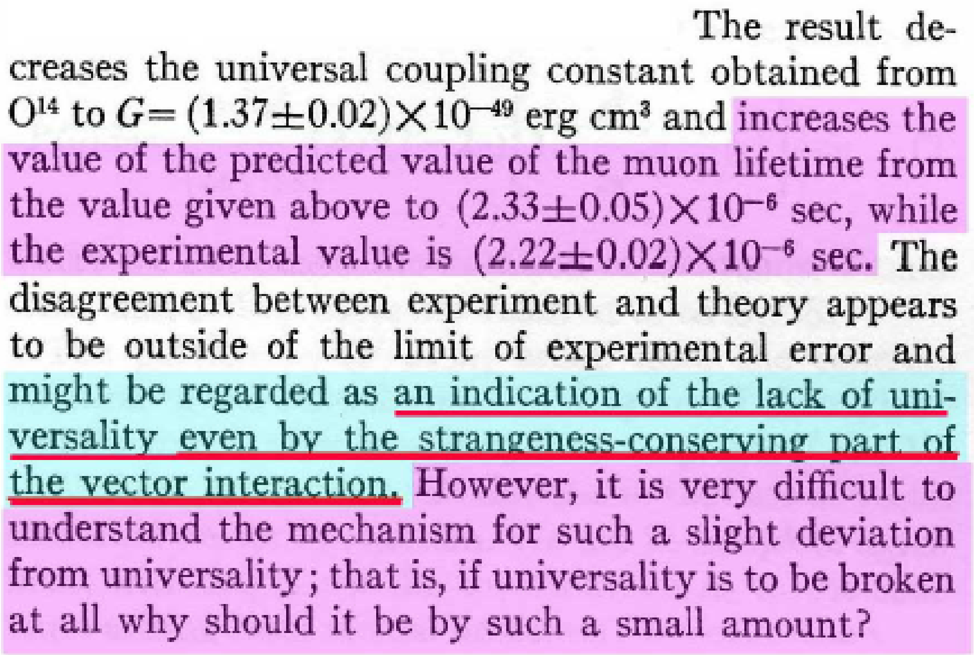
(Received June 11, 1958)

The corrections to muon decay due to electromagnetic interactions have been recalculated. ......

.... With the radiative corrections to muon decay given here, the predicted value of the muon lifetime using the universal theory is $(2.27\pm0.04)\times10^{-6}$ sec. As a preliminary to studying the decay of particles with structure, the β decay of the neutron is examined. This leads to an increase in the Coulomb F factor independent of the nuclear charge and of amount approximately 2.6%. As a result the universal coupling constant obtained from the decay of O^{14} is decreased to $G=(1.37\pm0.02)\times10^{-49}$ erg cm^3 and increases the value of the muon lifetime to $(2.33\pm0.05)\times10^{-6}$ sec.

The Second Problem

The radiative corrections tended to worsen the disagreement between the Fermi constant as measured in beta decay and in muon decay, making it serious.

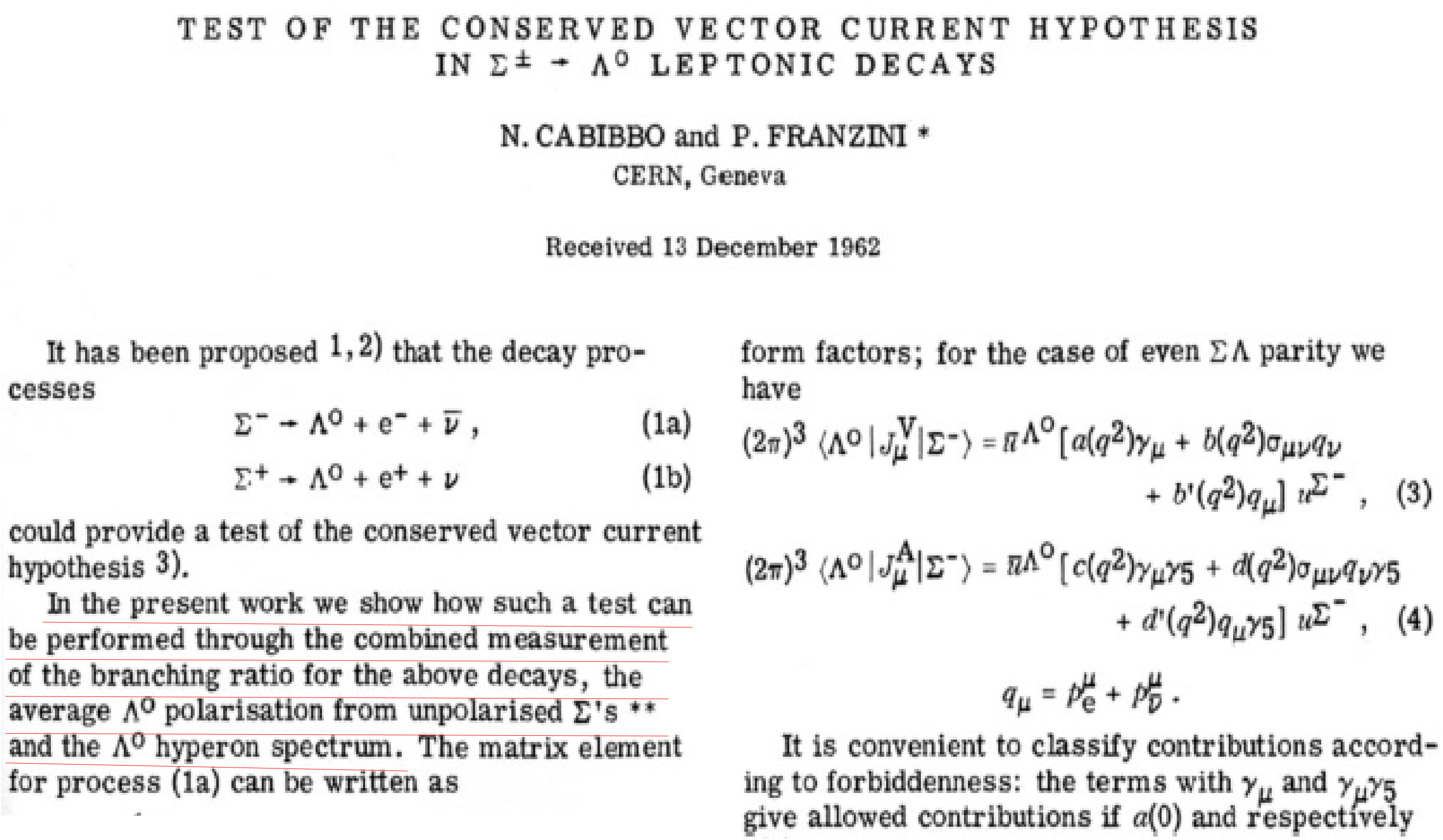


The result decreases the universal coupling constant obtained from O^{14} to $G=(1.37\pm0.02)\times10^{-49}$ erg cm^3 and increases the value of the predicted value of the muon lifetime from the value given above to $(2.33\pm0.05)\times10^{-6}$ sec, while the experimental value is $(2.22\pm0.02)\times10^{-6}$ sec. The disagreement between experiment and theory appears to be outside of the limit of experimental error and might be regarded as an indication of the lack of universality even by the strangeness-conserving part of the vector interaction. However, it is very difficult to understand the mechanism for such a slight deviation from universality; that is, if universality is to be broken at all why should it be by such a small amount?

Taking muon decay as the standard we have beta decay a few % weaker and hyperon semileptonic decays about 20 times weaker.

Those days Cabibbo was at CERN, and was very interested in weak decays, both on the experimental/phenomenological side...

CERN – winter 1962-63



TEST OF THE CONSERVED VECTOR CURRENT HYPOTHESIS IN $\Sigma^{\pm} \to \Lambda^{0}$ LEPTONIC DECAYS

N. CABIBBO and P. FRANZINI *
CERN, Geneva

Received 13 December 1962

It has been proposed [1,2] that the decay processes

$$\Sigma^- \to \Lambda^0 + e^- + \bar{\nu}\,, \qquad (1a)$$

$$\Sigma^+ \to \Lambda^0 + e^+ + \nu \qquad (1b)$$

could provide a test of the conserved vector current hypothesis [3].

In the present work we show how such a test can be performed through the combined measurement of the branching ratio for the above decays, the average Λ^0 polarisation from unpolarised Σ's ** and the Λ^0 hyperon spectrum. The matrix element for process (1a) can be written as

form factors; for the case of even $\Sigma\Lambda$ parity we have

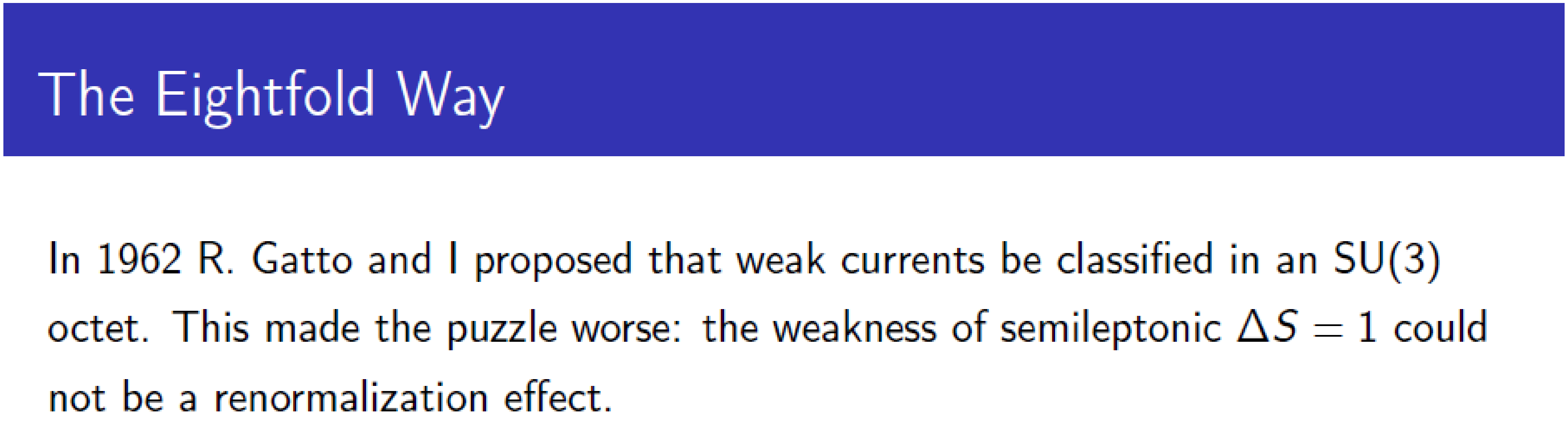
$$(2\pi)^3 \langle \Lambda^0 | J_\mu^V | \Sigma^- \rangle = \bar{u}^{\Lambda^0} [a(q^2)\gamma_\mu + b(q^2)\sigma_{\mu\nu}q_\nu + b'(q^2)q_\mu]\, u^{\Sigma^-}\,, \qquad (3)$$

$$(2\pi)^3 \langle \Lambda^0 | J_\mu^A | \Sigma^- \rangle = \bar{u}^{\Lambda^0} [c(q^2)\gamma_\mu\gamma_5 + d(q^2)\sigma_{\mu\nu}q_\nu\gamma_5 + d'(q^2)q_\mu\gamma_5]\, u^{\Sigma^-}\,, \qquad (4)$$

$$q_\mu = p_e^\mu + p_{\bar{\nu}}^\mu\,.$$

It is convenient to classify contributions according to forbiddenness: the terms with γ_μ and $\gamma_\mu\gamma_5$ give allowed contributions if $a(0)$ and respectively

Those days Cabibbo was at CERN, and was very interested in weak decays, both on the experimental/phenomenological side... and on a more theoretical side (the approximate SU(3) invariance of strong interaction had just been proposed):

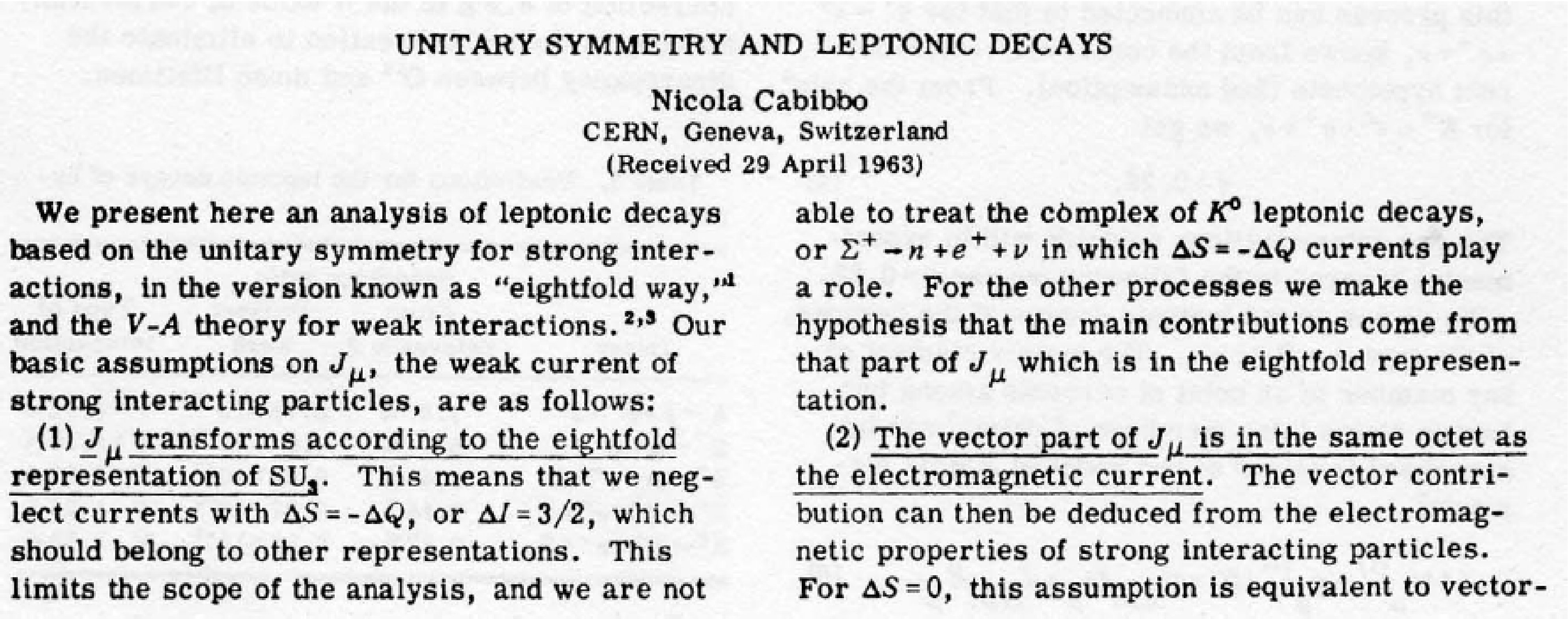


The Eightfold Way

In 1962 R. Gatto and I proposed that weak currents be classified in an SU(3) octet. This made the puzzle worse: the weakness of semileptonic $\Delta S = 1$ could not be a renormalization effect.

N.B.: before this work several people claimed that the weakness of $\Delta S=1$ processes could be attributed to strong interactions

Nicola, do something fundamental!



UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

We present here an analysis of leptonic decays based on the unitary symmetry for strong interactions, in the version known as "eightfold way,"[1] and the V-A theory for weak interactions.[2,3] Our basic assumptions on J_μ, the weak current of strong interacting particles, are as follows:

(1) J_μ transforms according to the eightfold representation of SU_3. This means that we neglect currents with $\Delta S = -\Delta Q$, or $\Delta I = 3/2$, which should belong to other representations. This limits the scope of the analysis, and we are not able to treat the complex of K^0 leptonic decays, or $\Sigma^+ \to n + e^+ + \nu$ in which $\Delta S = -\Delta Q$ currents play a role. For the other processes we make the hypothesis that the main contributions come from that part of J_μ which is in the eightfold representation.

(2) The vector part of J_μ is in the same octet as the electromagnetic current. The vector contribution can then be deduced from the electromagnetic properties of strong interacting particles. For $\Delta S = 0$, this assumption is equivalent to vector-

Thanks, Paolo…

The Eightfold Way

In 1962 R. Gatto and I proposed that weak currents be classified in an SU(3) octet. This made the puzzle worse: the weakness of semileptonic $\Delta S = 1$ could not be a renormalization effect. The missing clue, which I found the next year, was that one should not compare the strength of the two components of the hadronic weak current to the $\mu - \nu_\mu$ or $e - \nu_e$ current separately but together,

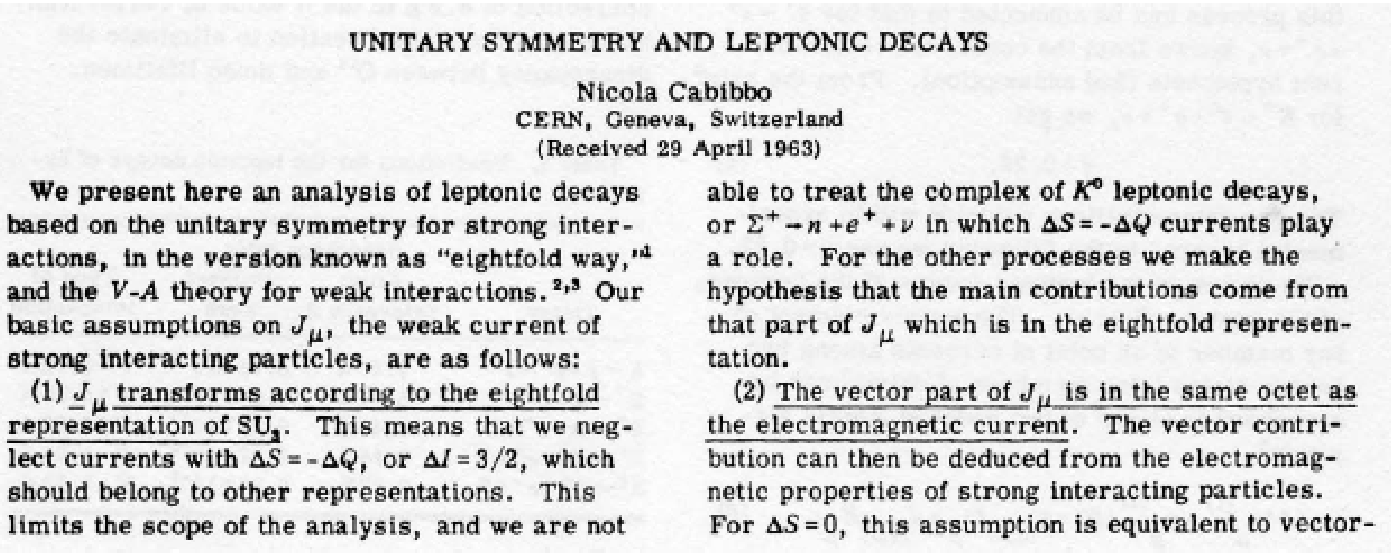
$$J^{\text{weak}} = J^{\mu-\nu_\mu} + J^{e-\nu_e} + \left(aJ^{\Delta S=0} + bJ^{\Delta S=1}\right) + \ldots$$

This led to the condition

$$a^2 + b^2 = 1 \qquad \text{or} \qquad a = \cos\theta, \qquad b = \sin\theta$$

and to a simultaneous solution of both problems: the $\Delta S = 1$ decays feed from a small decrease of the $\Delta S = 0$ beta decay.

The “Angle” paper



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The value of the angle θ was here determined in two different ways:

From Kl3 decays	$\theta = 0.26$
From the $\dfrac{K \to \mu\nu}{\pi \to \mu\nu}$ ratio	$\theta = 0.257$

Modern measurements of Kl3 decays lead to smaller values, and in 2008 the KLOE result is $V_{us} = sin(\theta) = 0.2237 \pm 0.0013$. The different value from $K \to \mu\nu$ is due to a violation of SU(3) symmetry, perfectly accounted by lattice QCD simulations.

Lattice Gauge Theory

Since 1984 (N.C, G. Martinelli, R. Petronzio, Nuc, Phys. B244:381) lattice gauge theory has been an important tool in disentangling the QCD aspects of weak interaction processes. One of the nicer results was the computation of f_π, f_K by the MILC collaboration (hep-lat 0406324)

$$\begin{aligned} f_\pi &= 129.3 \pm 1.1 \pm 3.5 \text{ MeV} \\ f_K &= 155.0 \pm 1.8 \pm 3.7 \text{ MeV} \\ f_K / f_\pi &= 1.201(8)(15) \end{aligned}$$

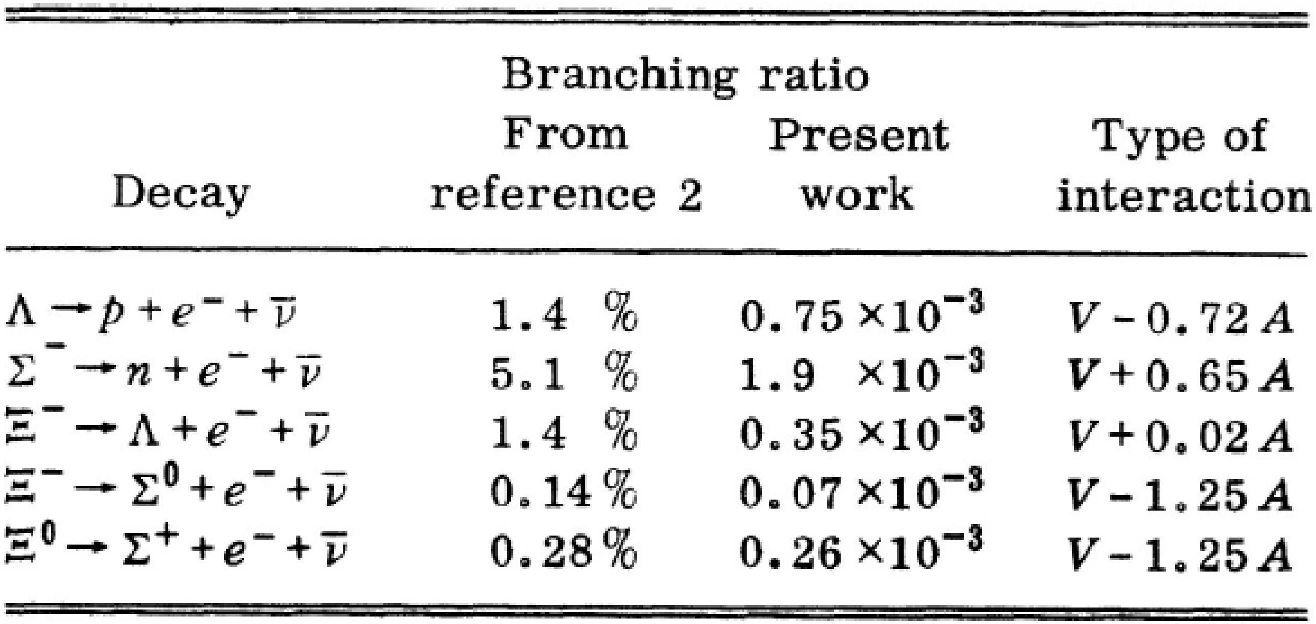
From these results Marciano (hep-ph 0402299) obtained

$$\sin\theta = 0.2236(30)$$

More accurate values originate from recent LQCD simulations and the KLOE experimental data.

Hyperon Semileptonic Decays

An important result of the "angle" paper was the prediction of the branching ratios and decay parameters for the possible $\Delta S = 1$ hyperon decays.



Decay	Branching ratio From reference 2	 Present work	Type of interaction
$\Lambda \rightarrow p + e^- + \bar{\nu}$	1.4 %	0.75×10^{-3}	$V - 0.72\,A$
$\Sigma^- \rightarrow n + e^- + \bar{\nu}$	5.1 %	1.9×10^{-3}	$V + 0.65\,A$
$\Xi^- \rightarrow \Lambda + e^- + \bar{\nu}$	1.4 %	0.35×10^{-3}	$V + 0.02\,A$
$\Xi^- \rightarrow \Sigma^0 + e^- + \bar{\nu}$	0.14 %	0.07×10^{-3}	$V - 1.25\,A$
$\Xi^0 \rightarrow \Sigma^+ + e^- + \bar{\nu}$	0.28 %	0.26×10^{-3}	$V - 1.25\,A$

These were checked over many years, with correct results on the $\Sigma^- \Rightarrow ne\bar{\nu}$ only appearing in the mid-eighties, and the first measurement of $\Xi^0 \Rightarrow \Sigma^+ e\bar{\nu}$ by the KTeV group, presented in 2001.

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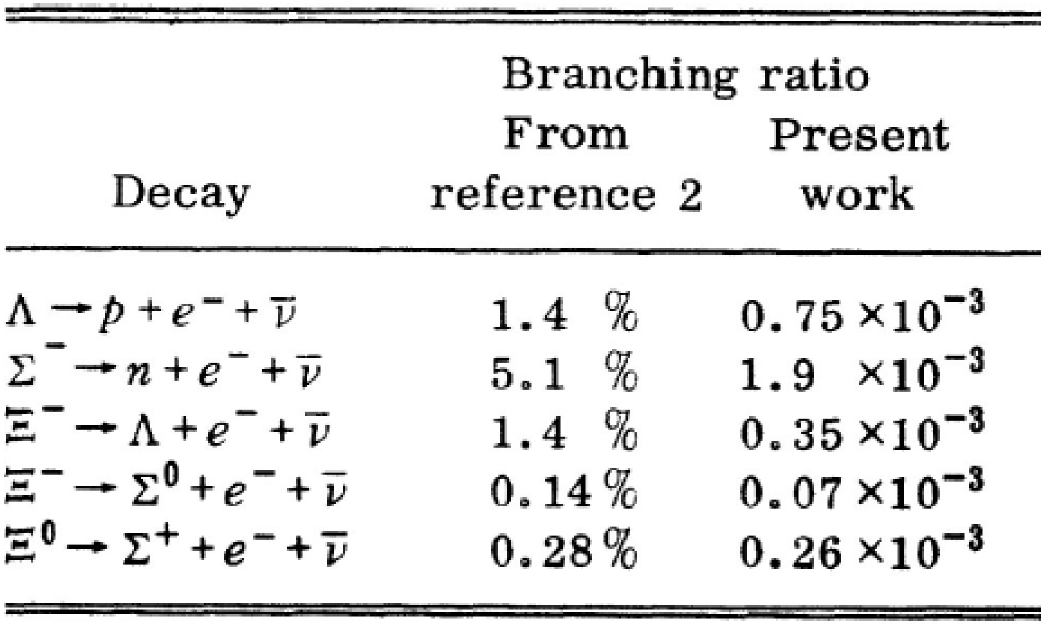


Decay	Branching ratio From reference 2	Branching ratio Present work	modern values
$\Lambda \rightarrow p + e^- + \bar{\nu}$	1.4 %	0.75×10^{-3}	$0.832(14) \cdot 10^{-3}$
$\Sigma^- \rightarrow n + e^- + \bar{\nu}$	5.1 %	1.9×10^{-3}	$1.017(34) \cdot 10^{-3}$
$\Xi^- \rightarrow \Lambda + e^- + \bar{\nu}$	1.4 %	0.35×10^{-3}	$0.563(31) \cdot 10^{-3}$
$\Xi^- \rightarrow \Sigma^0 + e^- + \bar{\nu}$	0.14 %	0.07×10^{-3}	$0.087(17) \cdot 10^{-3}$
$\Xi^0 \rightarrow \Sigma^+ + e^- + \bar{\nu}$	0.28 %	0.26×10^{-3}	$0.253(8) \cdot 10^{-3}$

These were checked over many years, with correct results on the $\Sigma^- \Rightarrow ne\bar{\nu}$ only appearing in the mid-eighties, and the first measurement of $\Xi^0 \Rightarrow \Sigma^+ e\bar{\nu}$ by the KTeV group, presented in 2001.

Board a Time Machine...

... and let events wooooosh by

Quarks

CP Violation

Deep Inelastic, e^+e^- colliders

Charm, J/Ψ , c-quark

Standard Model

The CKM matrix

Υ, b-quark, t-quark

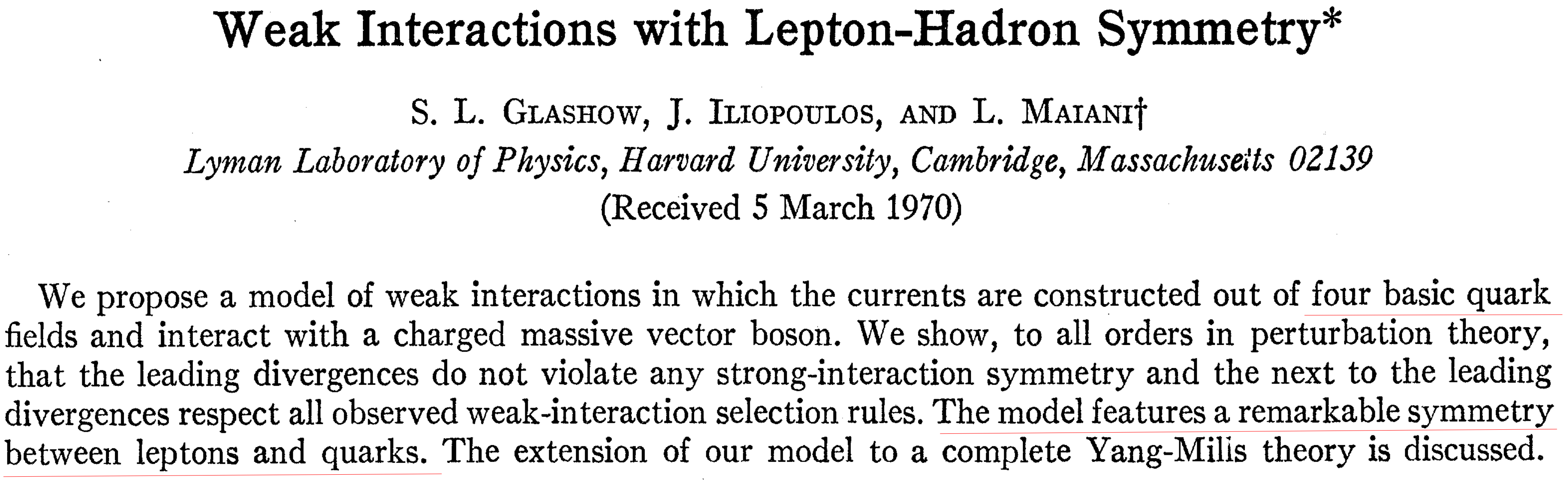
Neutrino Oscillations — Neutrino Mixing

……

Some key dates in flavour physics:

1964 Discovery of CP violation

1970 GIM (Glashow, Iliopoulos, Maiani):



Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

(Received 5 March 1970)

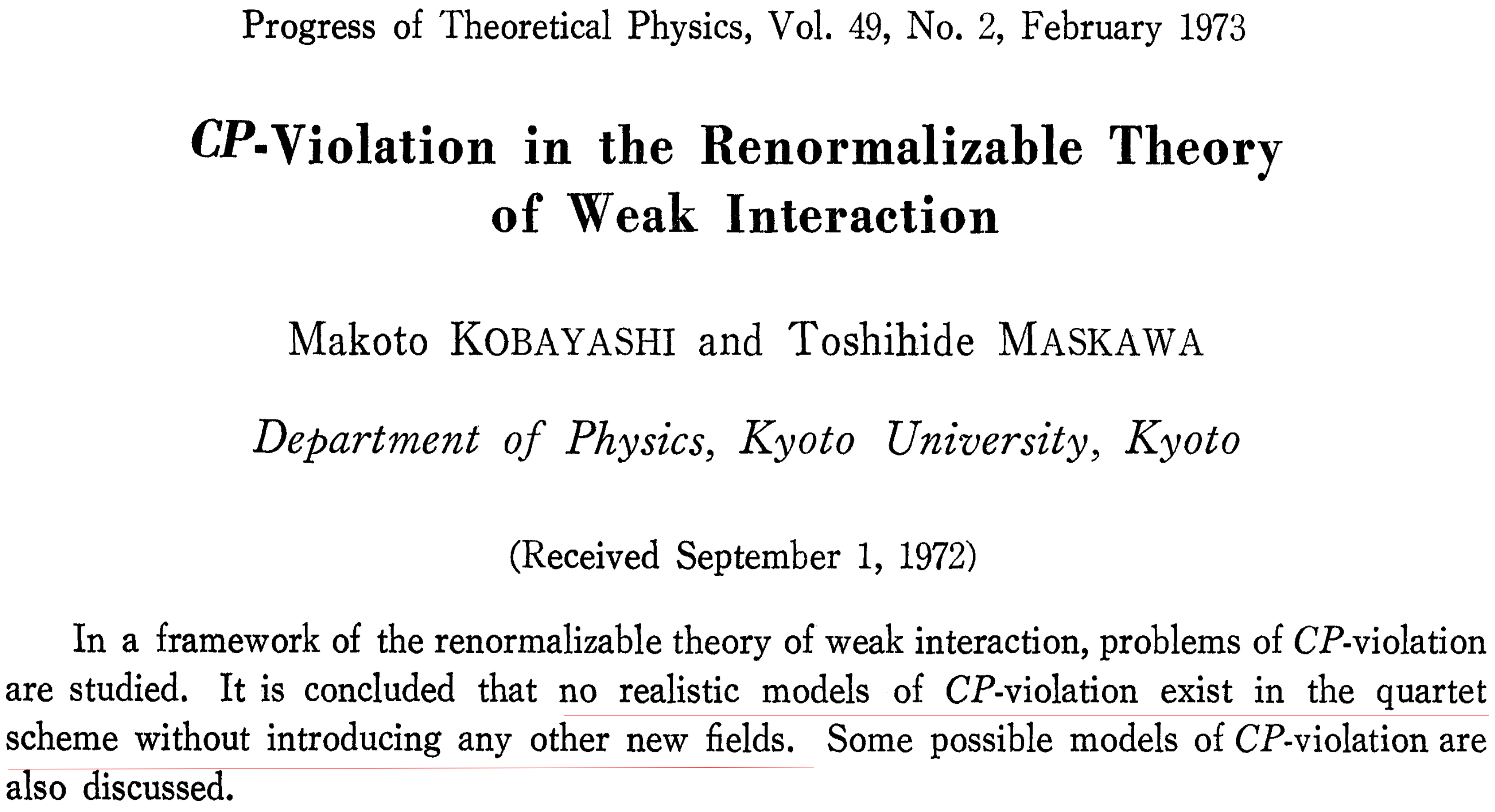
We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

from   to

$$J_\mu^{Weak} = (\cos\theta J_\mu^{\Delta S=0} + \sin\theta J_\mu^{\Delta S=1}) \longrightarrow (u,c)_L\, \gamma^\mu \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}_L$$

Some key dates in flavour physics:

1964 Discovery of CP violation
1970 GIM (Glashow, Iliopoulos, Maiani)
1971 Weinberg paper on SU(2)xU(1)
1973 Kobayashi, Maskawa:



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

Some key dates in flavour physics:

1964	Discovery of CP violation
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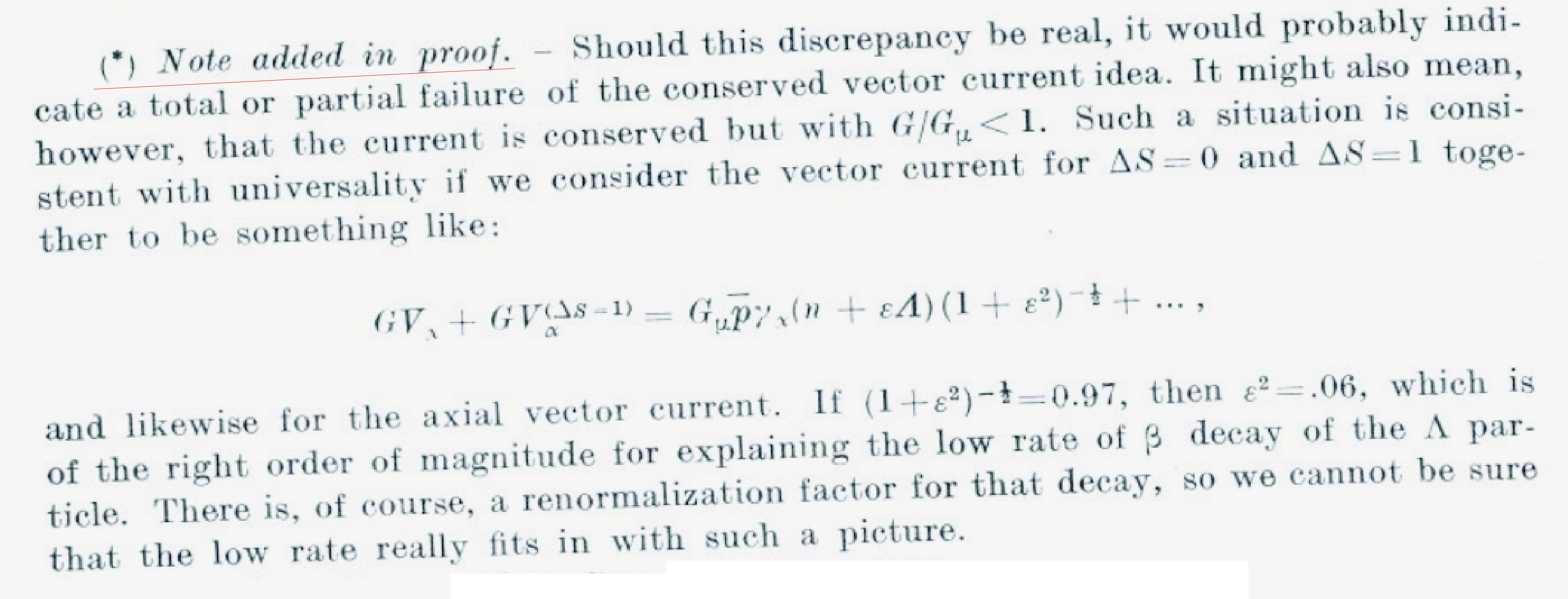
1971	Weinberg paper on SU(2)xU(1)
1973	Kobayashi, Maskawa
1974	Discovery of charm...
....	

The work of Cabibbo has been extremely influential, not only within flavour physics, but for the whole building of the Standard Model.

As many other people in our field, I'm strongly convinced that the 2008 Nobel prize to “KM” without “C” has been a great mistake.

Somebody claims this is because the idea of the “angle” was not totally original. In particular, it was proposed first (1962) in a paper by Gell-Mann and Levy (GL):



(*) *Note added in proof.* – Should this discrepancy be real, it would probably indicate a total or partial failure of the conserved vector current idea. It might also mean, however, that the current is conserved but with $G/G_\mu < 1$. Such a situation is consistent with universality if we consider the vector current for $\Delta S = 0$ and $\Delta S = 1$ together to be something like:

$$G V_\lambda + G V_\alpha^{(\Delta S=1)} = G_\mu \bar{p} \gamma_\lambda (n + \varepsilon \Lambda)(1+\varepsilon^2)^{-\frac{1}{2}} + \dots ,$$

and likewise for the axial vector current. If $(1+\varepsilon^2)^{-\frac{1}{2}} = 0.97$, then $\varepsilon^2 = .06$, which is of the right order of magnitude for explaining the low rate of β decay of the Λ particle. There is, of course, a renormalization factor for that decay, so we cannot be sure that the low rate really fits in with such a picture.

However, there is a tremendous gap between this footnote and the work by Cabibbo:

- it is not clear what happens to the other barions
- it is not clear what happens to the overall normalization
- even the relative normalization between n and Λ is wrong

and indeed there is not a single prediction from GL using this formula....

The key observation behind the work of Cabibbo is the hypothesis that the weak current transfroms as an SU(3) octet

$$J_\mu^{Weak} = J_\mu^{\mu-\nu_\mu} + J_\mu^{e-\nu_e} + (\cos\theta J_\mu^{\Delta S=0} + \sin\theta J_\mu^{\Delta S=1})$$

with $J_\mu^{\Delta S=0}$ and $J_\mu^{\Delta S=1}$ members of an SU(3) octet, together (their vector part) with J_μ^{em}

1. This solves the normalization problem (for the vector part)
2. It makes clear how to deal with all the barion octet
3. It shows in particular that even $\bar{p}n$ versus $\bar{p}\Lambda$ in the GL formula is not right, since SU(3) introduces a factor $\sqrt{3/2}$

R. Barbieri '09

Beside CKM-I

1) **Electron Positron Colliding Beam Experiments.**
N. Cabibbo, Raoul Gatto, (Rome U. & Cagliari U. & Frascati) . Dec 1961. 19pp.
Published in **Phys.Rev.124:1577-1595,1961**. (Reprinted in *Bologna 1984, Proceedings, Fifty years of weak-interaction physics* 612-630)

TOPCITE = 250+

“The Bible”

7) **Are neutrinos stable particles?**
John N. Bahcall, N. Cabibbo, A. Yahil, . Jan 1972. 3pp.
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TOPCITE = 100+

11) **Exponential Hadronic Spectrum and Quark Liberation.**
N. Cabibbo, (Rome U. & INFN, Rome) , G. Parisi, (INFN, Rome) . INFN-ROME-620, Jun 1975. 10pp.
A preliminary version has been presented at Workshop on Theoretical Physics, Erice, Italy, Apr 30 - May 7, 1975.
Published in **Phys.Lett.B59:67-69,1975**.

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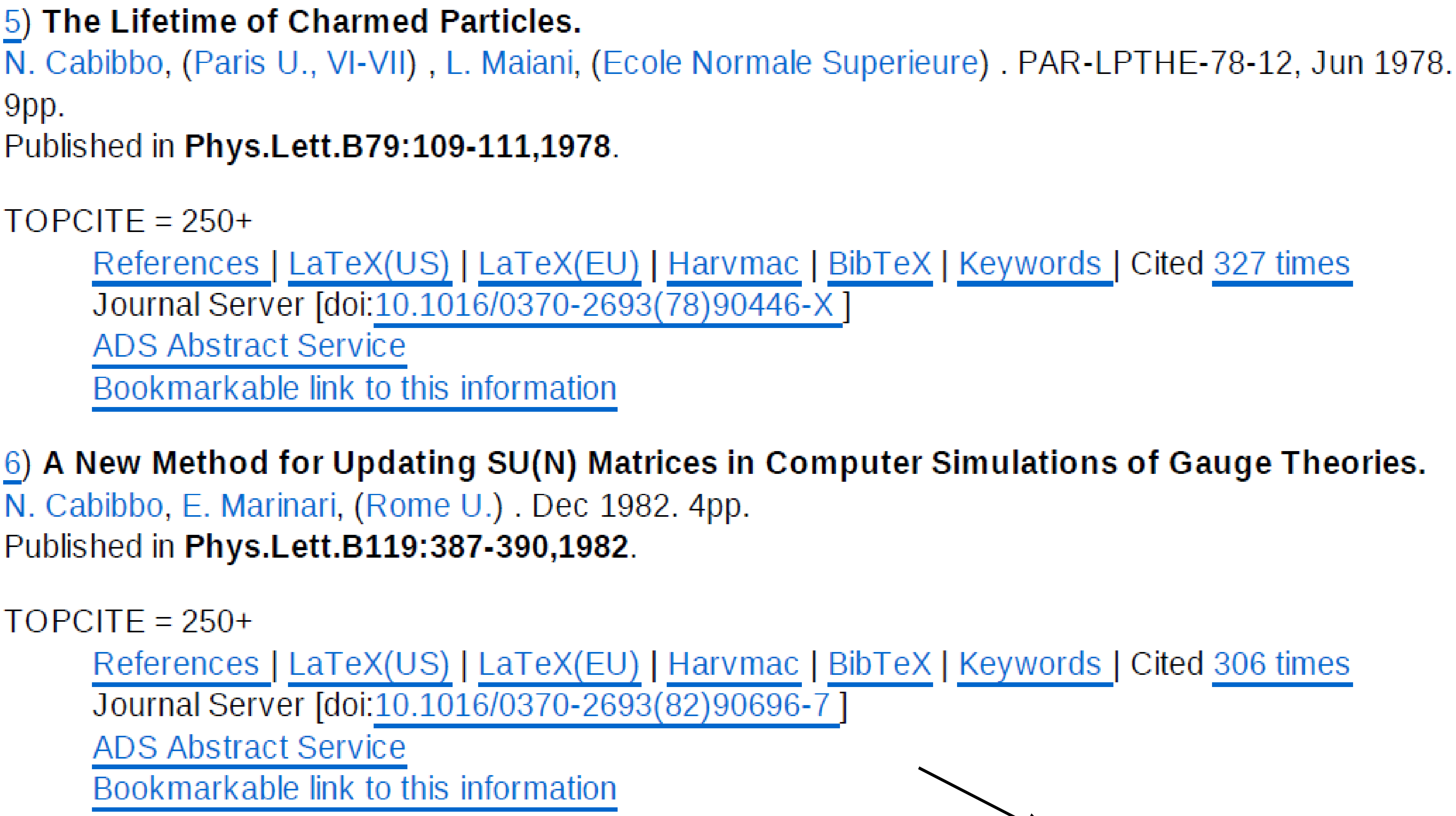
Beside CKM-II



5) **The Lifetime of Charmed Particles.**
N. Cabibbo, (Paris U., VI-VII) , L. Maiani, (Ecole Normale Superieure) . PAR-LPTHE-78-12, Jun 1978. 9pp.
Published in **Phys.Lett.B79:109-111,1978**.

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Journal Server [doi:10.1016/0370-2693(78)90446-X]
ADS Abstract Service
Bookmarkable link to this information

6) **A New Method for Updating SU(N) Matrices in Computer Simulations of Gauge Theories.**
N. Cabibbo, E. Marinari, (Rome U.) . Dec 1982. 4pp.
Published in **Phys.Lett.B119:387-390,1982**.

TOPCITE = 250+
References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords | Cited 306 times
Journal Server [doi:10.1016/0370-2693(82)90696-7]
ADS Abstract Service
Bookmarkable link to this information

→ APE

Beside CKM-III

3) **Bounds on the Fermions and Higgs Boson Masses in Grand Unified Theories.**
N. Cabibbo, (Rome U. & INFN, Rome) , L. Maiani, (CERN) , G. Parisi, (Frascati) , R. Petronzio, (CERN) . CERN-TH-2683, Jun 1979. 15pp.
Published in **Nucl.Phys.B158:295-305,1979**.

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References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords | Cited 522 times
Journal Server [doi:10.1016/0550-3213(79)90167-6]
CERN Library Record
Scanned Version (KEK Library)
Bookmarkable link to this information

2) **Leptonic Decay of Heavy Flavors: A Theoretical Update.**
Guido Altarelli, N. Cabibbo, G. Corbo, L. Maiani, (Rome U. & INFN, Rome) , G. Martinelli, (Frascati) . ROME-302-1982, Jun 1982. 30pp.
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TOPCITE = 500+

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Journal Server [doi:10.1016/0550-3213(82)90226-7]
pdgLive (measurements quoted by PDG)
Bookmarkable link to this information

Beside CKM-IV

President of INFN (1983-1992)

President of ENEA (mid '90s)

What I learned from him

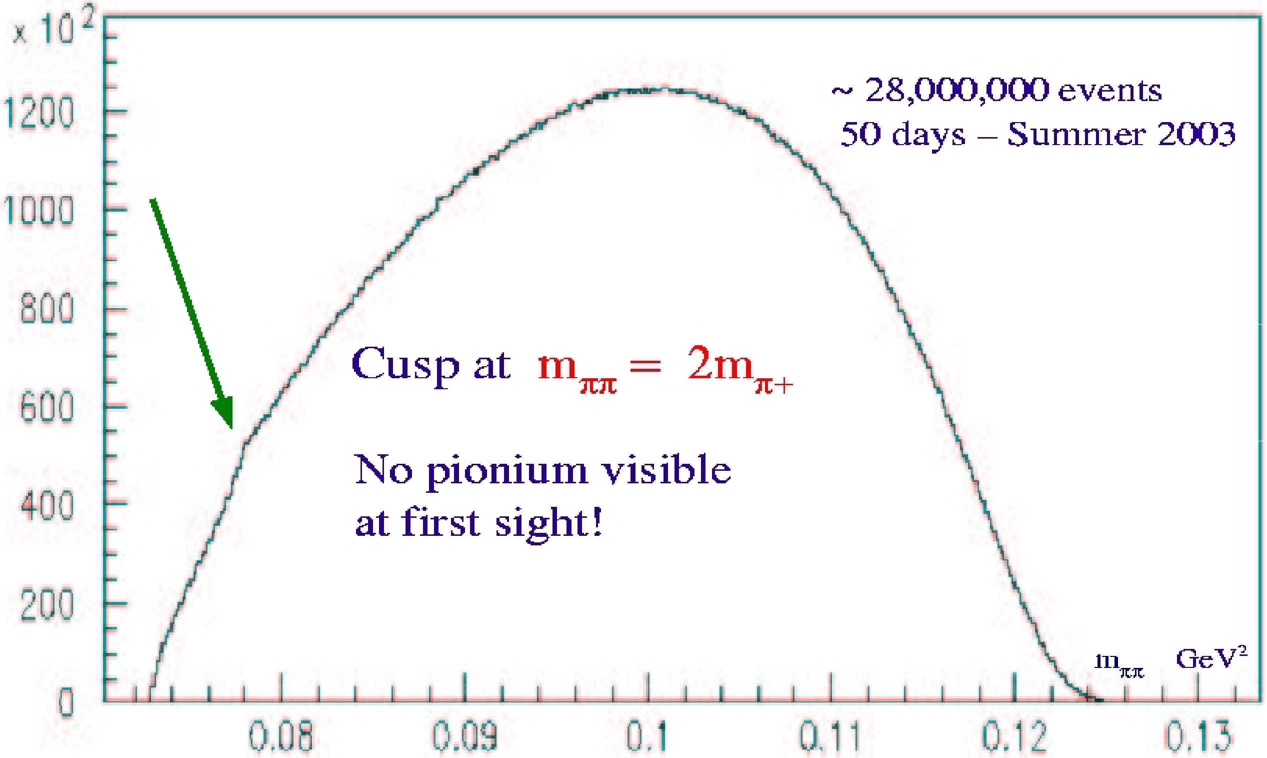
After a long interruption due to the important responsibilities ant INFN and ENEA, in the early 2000s Nicola went back to research and teaching at *"La Sapienza"*.

Because of his interest in flavour physics, not only on the theoretical side, in 2003 he decided to join the NA48 collaboration and in 2003/2004 he spent one sabatical year at CERN.

During this time (2004-2005) I had the pleasure and the honour to work with him.

The subject of our collaboration has been the study of the "cusp effect" in K→3π decays, and how to use this effect to make a precise measurement of ππ phase shifts at threshold.

NA48/2 data $K^{\pm} \dashrightarrow \pi^{\pm}\,\pi^{0}\,\pi^{0}$



~ 28,000,000 events
50 days – Summer 2003

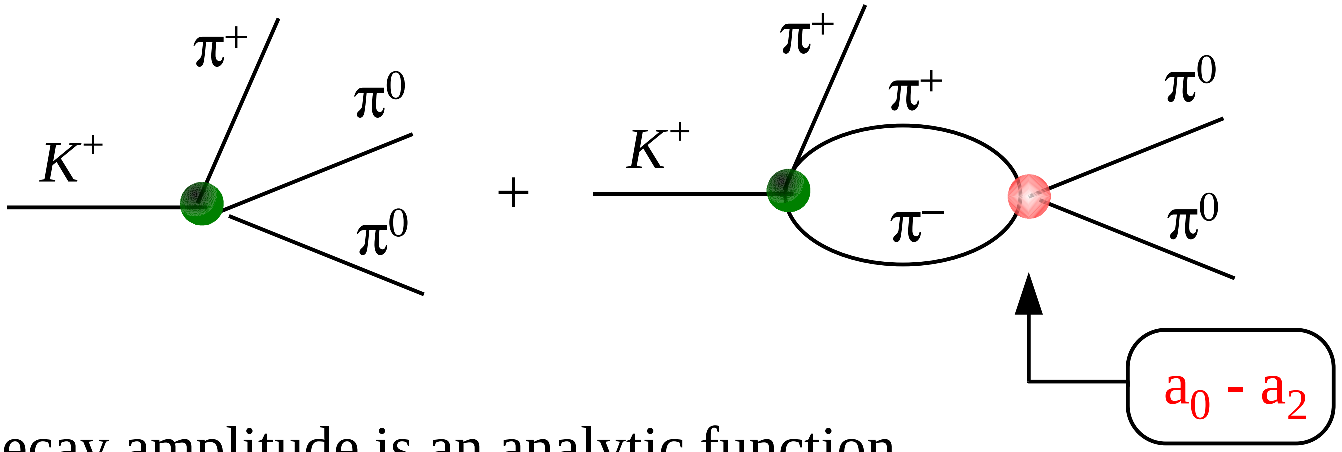
Cusp at $m_{\pi\pi} = 2m_{\pi+}$

No pionium visible
at first sight!

In 2004 the high
resolution of the
NA48/2 experiment
has allowed to observe
- for the first time -
a subtle & interesting
phenomenon

As soon as he saw these data, Cabibbo understood the origin of this discontinuity in term of a re-scattering effect, and that this effect could have been used to determine ππ phase shifts, at threshold, with high precision

Cabibbo, PRL '04



or $\pi^+\pi^-\to\pi^0\pi^0$ at threshold

- The decay amplitude is an analytic function of the di-pion invariant mass $s = (M_{\pi^0\pi^0})^2$
- The existence of a real intermediate state implies a discontinuity across the real axis for $s > s_0 = (2m_{\pi^+})^2$

$$T(s+i\varepsilon) - T(s-i\varepsilon) = i\,\rho_{\pi\pi}(s)\,V_{K\to3\pi}(s)\,V_{\pi\pi\to\pi\pi}(s)\,\Theta(s-s_0)$$

$$\downarrow$$

$$\sim v_{\pi+\pi-}(s) \sim (s-s_0)^{1/2}$$

Why are we interested in ππ scattering lengths ?

At low energies ($E \ll 1$ GeV) QCD is in a highly non-perturbative regime

- very difficult to describe the (low-energy) hadronic world in terms of partonic degrees of freedom.

However...

- the hadronic spectrum is very simple at low energies: only 3 (8) pseudoscalar fields separated by a mass gap from the heavier states
- the interactions among the pseudoscalar mesons become weak in the limit $E \to 0$

⬇

Reasonable to expect that QCD can be treated in a perturbative way even at low energies with a suitable choice of degrees of freedom:

(q, G) pQCD ⟷ (π, K, η) CHPT

[*perturbative @ high E*] [*perturbative @ low E*]

Chiral
Perturbation
Theory

Within this framework, the S-wave ππ scattering lengths

(defined, in the I-spin limit, by $T(\pi\pi_{I,I_3} \to \pi\pi_{J,J_3}) = 4 a_I v_{\pi\pi}(s)\, \delta_{I_3 J_3} \delta_{IJ} + O(v^3)$)

have a very special role:

$O(p^2)$: $$a_0\, m_\pi = \frac{7 m_\pi^2}{32\pi F_\pi^2} = 0.16 \qquad a_2\, m_\pi = \frac{-\, m_\pi^2}{16\pi F_\pi^2} = -\,0.05$$

Weinberg '79

$O(p^4)$: $$a_0\, m_\pi = 0.20 \pm 0.01 \qquad a_2\, m_\pi = -\,0.044 \pm 0.002$$

Gasser &Leutwyler '83

$O(p^6)$: $$a_0\, m_\pi = 0.217 \pm 0.005 \qquad a_2\, m_\pi = -\,0.0445 \pm 0.0010$$

Bijens, Colangelo, Ecker, Gasser & Leutwyler, '99

Roy eqs. [beyond $O(p^6)$]:

Colangelo *et al.* '01

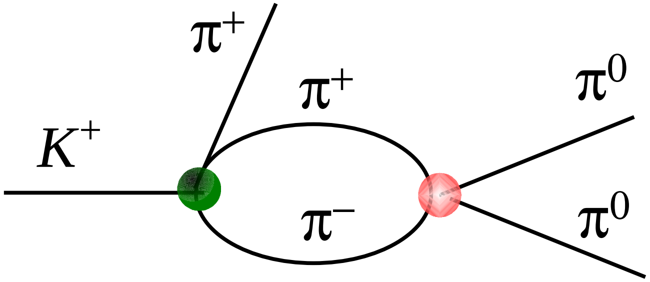
$$\boxed{\begin{aligned} a_0\, m_\pi &= 0.220 \pm 0.005 \\ (a_0 - a_2)\, m_\pi &= 0.265 \pm 0.004 \end{aligned}}$$

1.5 % relative error !

An almost unique example of a very precise prediction (obtained by means of analytic methods), for a truly non-perturbative quantity (from the point of QCD)

Toward a precise theoretical description of the cusp effect

A full calculation of K → 3π within CHPT is not very useful:



- slow convergece of the chiral expansion (even at the two-loop level)
- too many free parameters in the sector of weak interactions

...but we don't need to compute the full decay amplitude !

- possible to perform a systematic expansion in powers of the a_I of the amplitudes which determine the coefficient of the singularity

Ad hoc construction which maximize the available experimental info on K → 3π and use only:

Cabibbo & G.I., JHEP '05

- Unitarity & analyticity
- Smallness of the a_I
- Smallness of $v_{\pi\pi} = (s-s_0)^{1/2}$

$$\boxed{T(s) = A(s) + B(s)\,(s-s_0)^{1/2}}$$

A(s) & B(s) regular around s_0

$$T(s) = A(s) + B(s)\,(s-s_0)^{1/2}$$

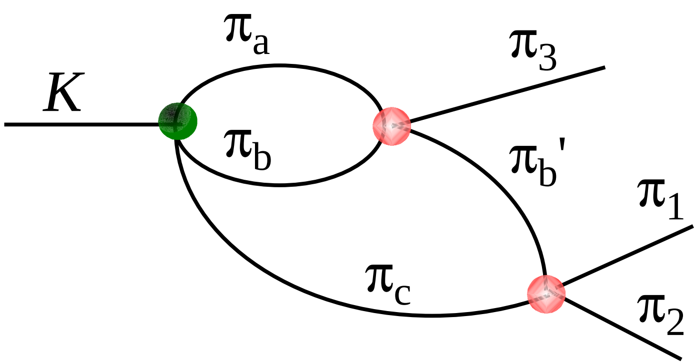
$\mathrm{Re}A(s) = O(1)$ exp. data

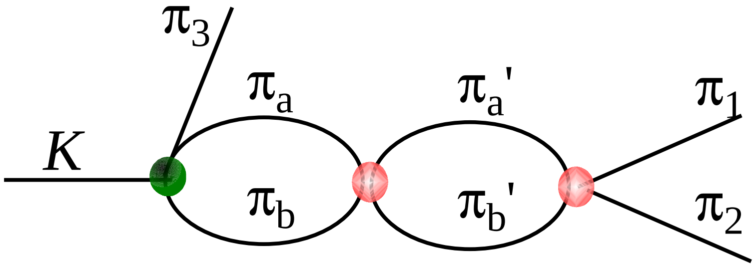
$\mathrm{Im}A(s) = O(a_I)$ one-loop

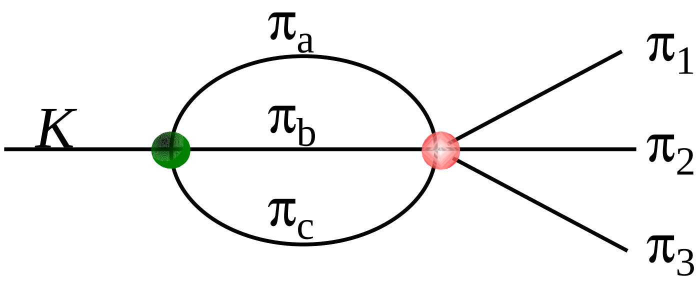
$\mathrm{Im}B(s) = O(a_I)$ one-loop

$\mathrm{Re}B(s) = O(a_I^2)$ two-loop

relevant 2-loop topologies:







Analysing the discontinuities of these diagrams, we have determined - in powers of the a_I up to $O(a_I^2)$ - the coefficients of the $(s-s_0)^{1/2}$ terms in the rate

- *What I learned from him*

Beside the success and the intrinsic interest of this work (the final data, published in 2009, have demonstarted the validity of our approach), this has been one of the most enjoiable, instructive, and pleasent collaborations I have ever had.

What I will never forget his the love of Nicola for real data and, most important, his “*research toward simplicity*” in the description of physical phenomena.

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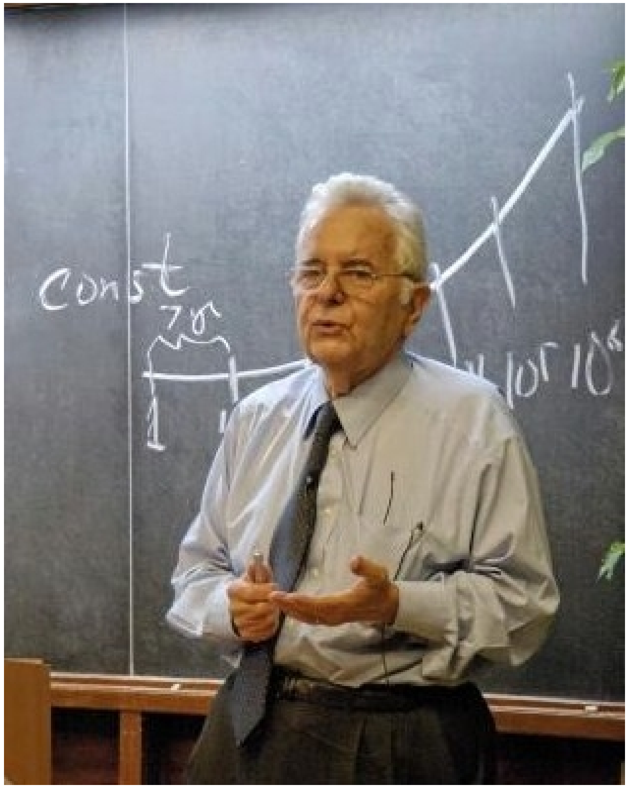

Thanks Nicola !