Claude Bouchiat Memorial Conference

Ecole Normale Superieure
Paris, July 12-13, 2023

Claude Bouchiat (1932-2021): from muon decay to the Standard Theory of fundamental particles

Luciano Maiani
Dipartimento di Fisica and Sezione INFN,
Università di Roma La Sapienza

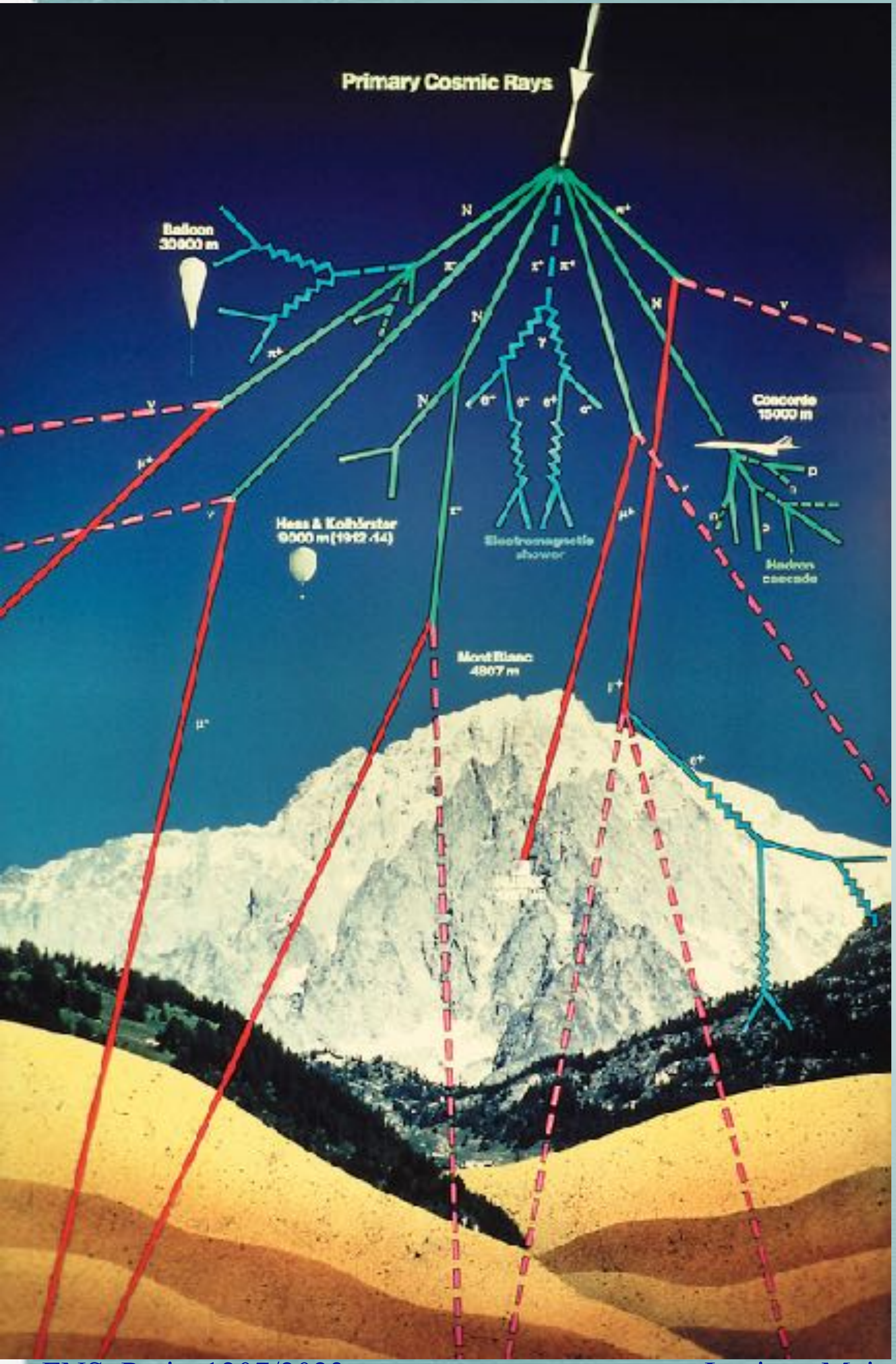
•Claude Bouchiat has been a protagonist of the creation of the Standard Theory, whose formation essentially filled up the time span of his career.

•With Phil Meyer and John Iliopoulos, he has been one of the driving forces in the group created by Maurice Lèvy in Orsay. The group moved to Ecole Normale in 1974 and since then has grown a remarkable population of bright theoretical physicists working in essentially all branches of modern particle theoretical physics, from phenomenology to supersymmetry, to string theory, to quote only the main subjects.

• Claude was close to the phenomenological aspects of the Standard theory, to the extent that he moved to experimental physics in the late Seventies when, with his wife Marie-Anne Bouchiat, he planned and started brilliant experiments to put into evidence the Parity Violation effects induced be the weak neutral currents in the radiative decays heavy atoms.

•Going down on the memory lane, I will follow Claude's works from his first steps in the late fifties on the theory of muon decay, with Louis Michel, to his contribution to fix the last problem of the Standard Theory, the cancellation of the Adler-Bell-Jackiw anomalies, which established definitely charge and color of each generation of quarks and leptons, and to the experiments on Parity Violation in atoms.

Where all started



- C. Anderson, S. Neddermeyer (1937) discover a new particle produced in the upper atmosphere at high altitude by the collisions of Cosmic Rays.
- 1946 (Roma): M. Conversi, E. Pancini e O. Piccioni, prove that the mesotron (μ particle, today) **is not** the π meson, the particle responsible for the nuclear forces, proposed by H.Yukawa;
- Many consider this discovery the birth of modern Elementary Particle physics

- Fermi, Marshak, etc. wore worried: *where is the pion ?*
- Pontecorvo asked a deeper question: *what is the mesotron ?*
- and proposed a surprising answer: ***the muon is a second generation electron***.

1. BOUCHIAT, C; MICHEL, L; THEORY OF MU-MESON DECAY WITH THE HYPOTHESIS OF NONCONSERVATION OF PARITY; PHYSICAL REVIEW **106** (1957)170

- With Louis Michel, Bouchiat investigated the decay properties of muon decay, an very efficient laboratory to explore the structure of the weak interactions.
- The Fermi weak interaction Lagrangian was simply the product of four fermion fields ψ connected by Dirac matrices, which Fermi, to keep the analogy with electromagnetism, restricted to be γ_μ matrices:

$$\mathscr{L} = \frac{G}{\sqrt{2}} \, (\bar{p}\gamma_\mu n) \, (\bar{e}\gamma^\mu \nu)$$

- Subsequent studies of nuclear and muon decays and the discovery of parity violation, led to complicate the gamma matrix structure, introducing all possible kinds of relativistically invariant products of two fermion field bilinears.
- Simplicity emerged at the end of the Nineteen Fifties, with the recognition that all β-decays then known, muon decay included, could be described by a V-A theory (Sudarshan and Marshak, Feynman and Gell-Mann)
- In *The Theory of Fundamental Interactions* (1961) Feynman could note:

…***every field*** ψ ***had to be replaced by*** $1/2(1-\gamma_5)\psi$

After 23 years, we are back to Fermi!

Ten years later (1967)…
…hopes of a basic theory for strong, e.m. and weak interactions

- Well established results:

$$q = \begin{bmatrix} u \\ d \\ s \end{bmatrix}$$

  - Gell-Mann-Zweig quarks in 3 flavours (baryons=qqq, etc.)
  - very small (~MeV) u and d quark masses were obtained from chiral symmetry breaking:

$$m_q = \mathrm{diag}(m, m, M)$$

  - Cabibbo theory of semileptonic decays with ΔS=0,1:

$$\mathcal{L}_F = \frac{G_F}{\sqrt{2}} J^\lambda J^+_\lambda$$
$$J^\lambda = \bar{\nu}_e \gamma^\lambda (1-\gamma_5) e + \bar{\nu}_\mu \gamma^\lambda (1-\gamma_5)\mu + \bar{u}\gamma^\lambda(1-\gamma_5) d_C$$
$$d_C = \cos\theta d + \sin\theta s$$

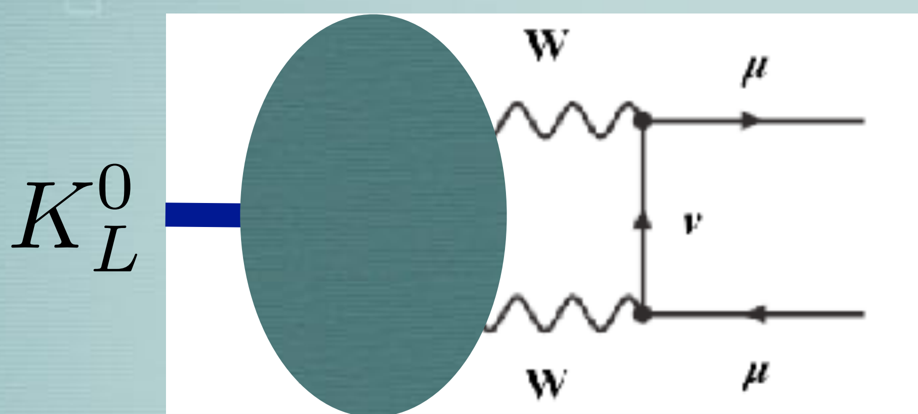
quarks: only one weak doublet

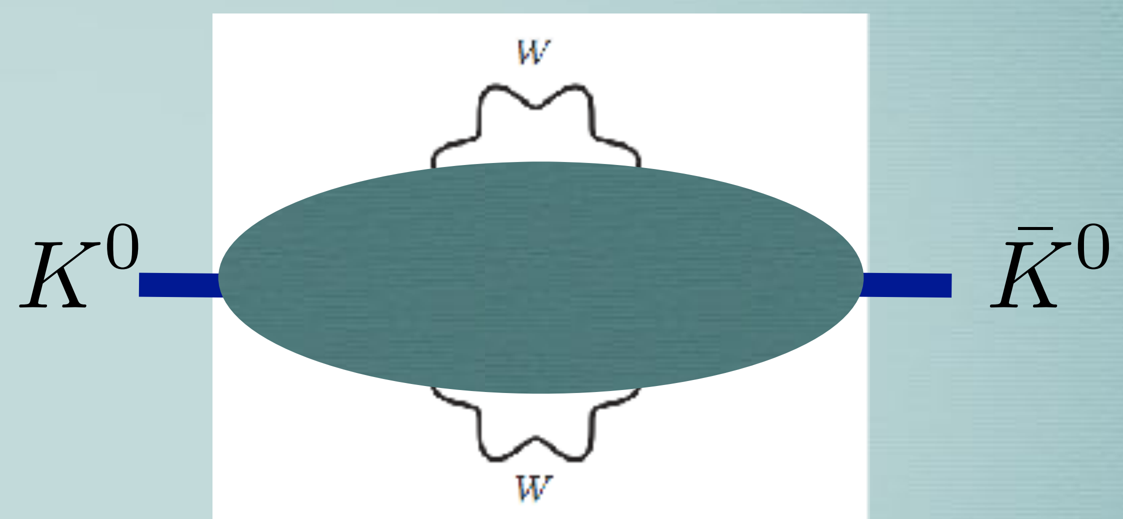
$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L ; (s_C)_L; d_R; u_R; s_R$$

- clouds:
  - do quark clash with Fermi-Dirac statistics? first ideas about color (Han-Nambu)
  - basic strong interactions: *gluon (abelian) mediated* ? *dual-like* (Veneziano model)
  - Fermi theory not renormalizable. W boson? strong interaction form factors?
- Schwinger ideas about EW unification + Yang-Mills:
  - Glashow's SU(2)⊗U(1) (1961)
  - Brout-Englert-Higgs Mechanism (1965) -> Weinberg-Salam (1967)
  - is Weinberg-Salam renormalizable?
- Embedding Cabibbo theory in SU(2) ⊗ U(1):
  - produces Flavour changing Neutral Currents
  - does Unification work for leptons only ?

2. *A bottom-up approach to higher order Weak Interactions: the G(GΛ²) puzzle, 1968*

- The discussion on higher order weak interactions was opened in 1968 by a calculation by Boris Ioffe and Evgeny Shabalin based on the algebra of currents in the quark model.
- I&S found that ΔS= ± 1 neutral currents and ΔS=2 amplitudes would result from higher order weak interactions, ***even in a theory with a charged W only.***
- Similar results were found by F. Low and by R. Marshak and coll.





- The result was based on current algebra commutators and shows that hadron form factors cannot help: ***current commutators imply hard constituents***;
- the amplitudes were found to be divergent, of order G(GΛ²), and in disagreement with experiments, unless limited by a surprisingly small ultraviolet cut-off Λ ≈ 3-4 GeV (from Δm_K)
- Attempts were made in 1968-69 to make the amplitude more convergent:
  - introducing more than one Intermediate Vector Boson (Gell-Mann, Low, Kroll, Ruderman) (too many were needed);
  - introducing negative metrics (ghost) states (T.D.Lee and G.C. Wick), of mass ≃ Λ!

C. Bouchiat, J. Iliopoulos and J. Prentki

DIVERGENCES OF WEAK NONLEPTONIC AMPLITUDES AND BREAKING OF SU3XSU3;
NUOVO CIMENTO A56(4) (1968) 1150

- The structure of strong and weak amplitudes in the IVB theory, in presence of higher order weak corrections is:

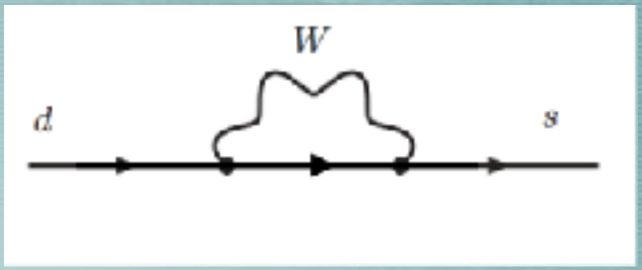
$$A_s = A_s^{(0)} + (G\Lambda^2)A_s^{(1)} + \dots ;$$
$$A_w = A_w^{(1)}GM^2 + A_w^{(2)}GM^2(G\Lambda^2) + \dots$$

where $GM^2 \sim 10^{-5}$ and Λ the ultraviolet cut-off.

- The paper analyses the $G\Lambda^2$ corrections to the strong amplitude A_s, which could produce Parity and Strangeness non-conservation effects, requiring a value of the cut-off even smaller than those found by Ioffe and Shabalin in the one-loop corrections to A_w.
- They assume that chiral SU(3) ⊗ SU(3) breaking is described by the $(\mathbf{3}, \bar{\mathbf{3}}) + (\bar{\mathbf{3}}, \mathbf{3})$ representation, made by scalar and pseudoscalar densities $u_i = (\bar{q}\lambda^i q), v_i = (\bar{q}\lambda^i\gamma_5 q)$
- and find that P and S violating terms of order $(G\Lambda^2)$ are proportional to $v_3, u_{6,7}, v_{6,7}$
- These operators are all of the form $\partial^\mu J_\mu$, J_μ= Vector or Axial current, and therefore do not contribute to on-shell matrix elements.

Divergent corrections to quark mass: facts and wishful thinking (1969)

- The divergent result found by Bouchiat *et al*. is due to the weak renormalization of quark mass. Gatto *et al*. tried to determine the Cabibbo angle by requiring a cancellation of the divergent term.



R. Gatto, G. Sartori and M. Tonin, Phys. Lett. B **28** (1968), 128

- In 1969, with Cabibbo we made a full analysis of the weak correction to the quark mass hamiltonian

N. Cabibbo, L. Maiani, Phys. Rev. D **1** (1970), 707

- The starting point was the chiral breaking and the Cabibbo current

$$H_m^{(0)} = \bar{q}_L m_q q_R + h.c.; \; J_\mu = \bar{q}_L \gamma_\mu C(\theta) q_L. \quad C(\theta) = \begin{pmatrix} 0 & \cos\theta & \sin\theta \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- The weak corrections modify $H_m^{(0)} \to H_m = \bar{q}_L(m_q + \xi m_q\{C, C^\dagger\})q_R + h.c. \; (\xi \propto G\Lambda^2)$
Non diagonal terms correspond to the four-divergences of Bouchiat *et al*. and can be eliminated by an appropriate chiral rotation. Indeed, one can always find U and V such that: $H_m = \bar{q}_L V^\dagger \left(m_q + \xi m_q\{C, C^\dagger\}\right) U q_R + h.c. =$ real, diagonal → no P, S violation;

- The weak current is also renormalized, according to:
$J_\mu \to J_\mu^{phys} = \bar{q}_L \gamma_\mu V^\dagger C(\theta) V q_L = \bar{q}_L \gamma_\mu C(\bar{\theta}) q_L$

facts and wishful thinking (1969) (cont'd)

1. $$H_m = \bar{q}_L V^\dagger \left(m_q + \xi m_q \{C, C^\dagger\} \right) U q_R + h.c. = \text{real, diagonal}$$
2. $$J_\mu^{phys} = \bar{q}_L \gamma_\mu V^\dagger C(\theta) V q_L = \bar{q}_L \gamma_\mu C(\bar{\theta}) q_L$$

- We found two result:
  - the correction to H_m produces a violation of strong-isospin, $m_u \neq m_d$, of non electromagnetic origin;
  - such a term had been suggested by Coleman and Glashow and supported by the values of the isospin violating hadron mass differences (e.g. $m_{neutron} > m_{proton}$, never explained as an electromagnetic effect)
  - We noted that the ***fixed point of the transformation***: $\bar{\theta} = \theta$ corresponds to a value very close to the observed Cabibbo angle, $\tan\theta \simeq 0.22$
  - could this be considered a legal "calculation" of the Cabibbo angle ??

3. Discussions at Harvard (1969-70)

- The Ioffe-Shabalin problem was still on the table at the end of 1969, when I moved to Harvard and met with John Iliopoulos, at work with Shelly Glashow on the $G\Lambda^2$ corrections

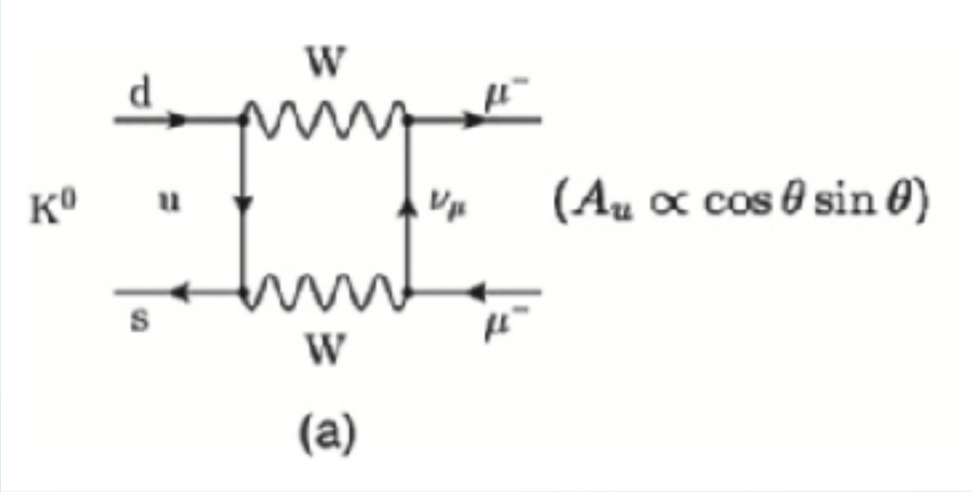
L.Bonolis, L. Maiani, Eur. Phys. J. H **42** (2017) 611

• So, we discussed and discussed, apparently getting nowhere. Usually two of us arguing against the one at the blackboard.

•But during our discussions a change in paradigm occurred.

• Previous works had been done in the framework of the "algebra of currents", but slowly we began to phrase more and more our discussion in terms of quarks

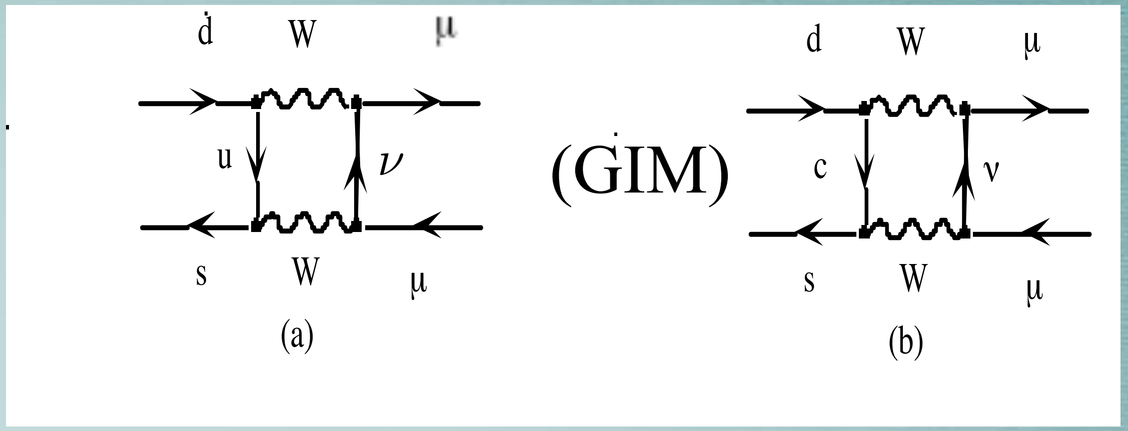
• In quark language, the Ioffe-Shabalin problem for $K^0 \to \mu + \mu-$ is represented by the box diagram in the Figure. The divergent amplitude is proportional to the product (cos θ sin θ) of the couplings of quarks d and s to the u quark, as required by the Cabibbo theory



- By January 1970 we got convinced that the weak interaction theory had somehow to be modified. Once we realised that, the solution was just under our eyes.
- A fourth quark of charge +2/3, called the *charm* quark, had been introduced few years before by Bjorken and Glashow (and by others), for entirely different reasons
- In the weak interaction, the charm quark was coupled in a doublet to the s_C quark left out by Cabibbo,

Starting from the Ioffe-Shabalin diagram…

- The exchange of the charm quark provides an additional diagram whose divergent part is proportional to $(-\sin\theta\cos\theta)$.
  - The sum of the two diagrams is ***finite*** and has exactly the Ioffe-Shabalin form with: $\Lambda^2 \sim (3\ \mathrm{GeV})^2 = m_c^2 - m_u^2$
  - The first computation of a weak interaction loop !
- The anomalously low cutoff is the magnitude of the mass of the particles that contain the charm quark.



- The weak charged current of the new theory is: $J_\mu^W = \bar{q}_L \gamma_\mu C q_L$ $\quad C = \begin{pmatrix} 0 & 0 & +\cos\theta & +\sin\theta \\ 0 & 0 & -\sin\theta & +\cos\theta \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$

- The weak isospin properties of quarks display a full ***lepton-quark symmetry***:

$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L ; \begin{pmatrix} c \\ s_C \end{pmatrix}_L ; (d_C)_R; (s_C)_R; u_R; c_R$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L ; \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L ; e_R; \mu_R$$

- The neutral weak current is $J_\mu^3 = \bar{q}_L \gamma_\mu [C, C^\dagger] q_L$, and is ***diagonal in flavour***: Electro-Weak unification, including quarks, is possible.

Back from the future

- In January 1970, Cabibbo was spending a semester in the Institute for Advanced Studies. With my wife, we took a bus from Boston to Princeton, to visit him and tell him about the GIM story.
- With Nicola, we came back to our work on quark mass renormalization. How would it look like in the new weak interaction theory with charm?
- The answer was easy to find and clear. The weak correction due to the charged currents is determined by the new 4x4 matrix C which describes $u, c \to d, s$ transition, and it was proportional to $\{C, C^\dagger\} = 1$!
- There was no renormalization, no fixed point in θ. And no "computation" of the Cabibbo angle was possible.
- Isospin violation had disappeared from charged current effects, but it *was contained in the contribution of the neutral weak current*, proportional to the weak hypercharge=electric charge for R-handed u and d quarks. Thus the idea of an isospin violation from weak interaction was still valid.
- The result was confirmed by Weinberg in his analysis of the renormalization of the Weinberg-Salam model.

S. Weinberg, Phys. Rev. D **8** (1973) 605

4. C. Bouchiat, J. Iliopoulos and P. Mayer

ANOMALY-FREE VERSION OF WEINBERG'S MODEL
PHYSICS LETTERS B **38** (1972). 519

- 1972, 't Hooft and Veltman proved the renormalization of the Weinberg Salam Theory

G. 't Hooft, M. J. G. Veltman, Nucl. Phys. B **44** (1972), 189

- Bouchiat *et al.* addressed the problem of Adler-Bell-Jackiw anomalies.

- As John wrote, *The term (anomaly) is slightly misleading, as it may give the impression that something contrary to common sense has happened. The real reason is that going from the classical equations to the quantum theory involves a series of steps which often include a limiting procedure, for example the limit of some parameter, the cut-off, going to infinity. This limit, although well defined, may not respect some of the symmetries of the classical equations.*

J. Iliopoulos, in *The Standard Theory of Particle Physics,* Edts. L. Maiani and L. Rolandi, World Scientific (2004) **ISSN 1793-1339**.

- The axial vector anomaly corresponds to a non-renormalizable term, therefore it has to cancel between leptons and quarks
- BIM find $\mathscr{A} = Tr[\{C^\dagger, C\}Y] +$ same for leptons.
- For two generations: $\{C^\dagger, C\} = 1,\ Y = T_3 + Q$, and one has $\mathscr{A} = \sum Q_{quark} + \sum Q_{lepton}$

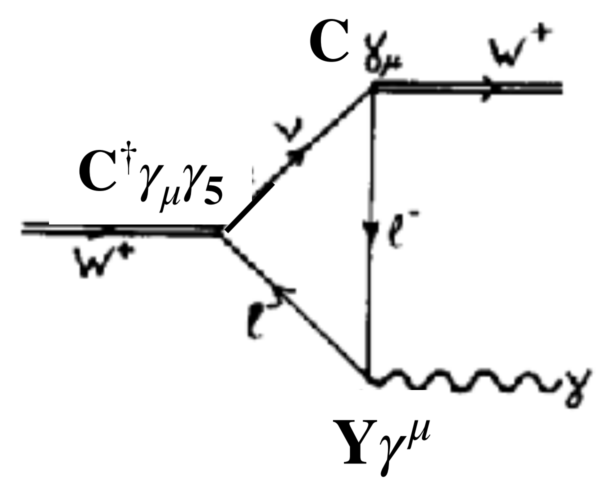


Fig. 3. Diagram giving rise to an anomaly in a theory involving the known currents of leptons and quarks

- *.. there must be charm, quarks come in three colours and are fractionally charged* (in a letter from J. Ilopoulos to me, 1972)

1972-1976: The crucial years of the Standard Theory

- In 1972, charm was generally accepted

  see J. R. Primack, Proc. of the XVI Int. Conf. on HEP, Chicago 1972, eConf **C720906V2**,319

- QCD with color octet gluons was proposed by Bardeen, Fritzsch, Gell-Mann and Leutwyler

  H. Fritzsch and M. Gell-Mann, Proc. of the XVI Int. Conf. on HEP, Chicago 1972, eConf **C720906V2**} 135; H. Fritzsch, M. Gell-Mann and H. Leutwyler, Phys. Lett. B **47** (1973), 365.

- 1973. The Gargamelle Collaboration discovers *muonless neutrino reaction*s, which proved the existence of the Weak Neutral Currents and gave the first experimental confirmation of Electro-Weak Unification

  F. J. Hasert *et al.* [Gargamelle Neutrino], *Observation of neutrino-like interactions without muon or electron in the Gargamelle neutrino experiment*, Physics Letters B **46** (1973) 138

- In the same year, the discovery of asymptotic freedom of the Yang- Mills theory by Gross and Wilczeck and by Politzer.

  D. Gross, F. Wilczeck, Phys. Rev. Letters **30** (1973)1343; D. Politzer, Physical Review Letters **30** (1974) 1346.

- 1974. The discovery of J/Ψ by Sam Ting at Brookhaven and Burt Richter at SLAC.

- 1976. First observation of charmed, D, D^* mesons.

- Lederman at Fermi Lab sees bottomonium ($\bar{b}b$) states, Martin Perl discovers the heavy lepton τ at SLAC : the third generation predicted by Kobayashi and Maskawa (1973) to explain CP violation

Late Seventies: Roma-Paris-Utrecht collaboration

L.Bonolis, L. Maiani, Eur. Phys. J. H **42** (2017) 645

•With John Iliopoulos in Paris, close relations were established between Rome and the group of Phil Meyer in Orsay. When, in 1974, Meyer's group moved from Orsay to École Normale Supérieure, Guido Altarelli and I were visiting, living in rue d'Ulm (with Keith Ellis also around).

•The discovery of the J/Ψ raised a lot of questions and we (Rome and Paris) accepted to go to Utrecht to discuss with Tini Veltman and Gerard 't Hooft, a meeting which became the annual *Triangular Meeting Paris-Rome-Utrecht*, rotating among the three towns.

•Guido took a crucial sabbatical at ENS in 1976-1977 where he and Parisi wrote the paper on deep inelastic scattering, with the famous Altarelli-Parisi equations (the most quoted French theoretical paper of that year!).

G.Altarelli, G. Parisi, *Asymptotic Freedom in Parton Language*. Nucl. Phy. B **126** (1977) 298.

•Nicola Cabibbo followed, visiting Paris VI during my sabbatical at ENS, 1977–1978. It was remarked, at that time, that Rome people saw CERN only from the airplane, flying to Paris.

•When at ENS, we all lived under the surveillance of Claude Bouchiat and the quiet but firm protection of Phil Meyer.

5. BOUCHIAT, MA; BOUCHIAT, CC; WEAK NEUTRAL CURRENTS IN ATOMIC PHYSICS; PHYSICS LETTERS B **48** (1974)111

C. Bouchiat (1974) WEAK NEUTRAL CURRENTS IN ATOMIC PHYSICS

$$V_{AV} = -\frac{G_F}{2\sqrt{2}}\left(\frac{\vec{\sigma}\cdot\vec{p}_e}{m_e}\,\delta^3(\vec{r}) + \delta^3(\vec{r})\,\frac{\vec{\sigma}\cdot\vec{p}_e}{m_e}\right)\times$$
$$\times\left[C_{Vp}Z + C_{Vn}(A-Z)\right]$$

(In the above expression m_e, $\vec{r}$, $\vec{p}_e$, $\vec{\sigma}$ are the mass, position, momentum and spin of the electron, respectively).

$$C_{Ap} = -C_{An} = 1.25\left(2\sin^2\theta_W - \frac{1}{2}\right)$$

$$C_{Tp} = C_{Tn} = 0$$

$\bar{s}s$, $\bar{c}c$ neglected

- Mixing between $s^{\frac{1}{2}} - p^{\frac{1}{2}}$ states
- Asymmetry in the scattering of polarised light

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

- Results produced by Marie-Ann, Claude *and coll*. in the years 1974 - 1979 have been reported in conferences and schools.

BOUCHIAT, C; NEUTRAL CURRENT INTERACTIONS IN ATOMS; Contribu? on to : Workshop on Neutral Current Contribution in Atoms (1979) 357-369

Deep-inelastic scattering of polarised electrons

•A very clear asymmetry was obtained in deep-inelastic e-p scattering experiments at SLAC in 1978

C. Y. Prescott *et al., Parity Nonconservation in Inelastic Electron Scattering,* Phys. Lett. B **77** (1978), 347

- *Finally, parity-violation in the neutral currents was discovered at the expected level in electron-nucleon scattering at SLAC in 1978, and after that most physicists took it for granted that the electroweak theory is essentially correct.*

S. Weinberg, *The Making of the standard model,* Eur. Phys. J. C **34** (2004), 5
CERN Courier, Neutral currents and W and Z: a celebration , Dec. 2003

Within 1978, all elements of the Standard Theory were on the table

- A Golden Age of experimental physics started:
  - New Machines: $P\bar{P}$ collider, LEP, LHC
  - the discovery of Intermediate bosons,
  - neutrino oscillations and masses,
  - Dark Matter…
  - the Higgs Boson
- Claude was a reference figure, for the formation and selection of bright, new, theorist, at ENS and elsewhere;
- Theory went into the mode Beyond the Standard Theory…where it still is
- … but: we are not sure we understand really where are we going.