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Doing electroweak physics with Roberto

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Summary. — Friendship and Collaboration with Roberto, while the Standard Theory was unfolding under our eyes.

At the end of the sixties, dual models dominated the scene as the theory of strong interactions. However, the years 1971-1973 brought decisive discoveries [1].

- 1971, 't Hooft and Veltman showed that the Weinberg-Salam theory is renormalisable;
- 1972, Bouchiat, Iliopoulos and Meyer proved the cancellation of Adler anomalies in the electroweak theory with four quarks. In a letter from John, *there must be charm, quarks have color and are fractionally charged*;
- 1973 the discovery of neutral currents by Gargamelle at CERN;
- ... and in the same year came the discovery of asymptotic freedom of the Yang-Mills theory by Gross and Wilczeck and Politzer.

Shortly after, the idea of color interaction of quarks was put forward by Fritzsch, Gell-Mann and Leutwyler. In three years, the paradigm of particle interactions shifted completely towards field theory, a shining example of what Thomas Kuhn in 1962 had called a scientific revolution.

In 1974, the discovery of the J/Ψ opened another chapter: heavy fermions, initiated with charm and later continued with the heavy lepton, beauty and top.

The Standard Theory was taking form, everybody became electroweak & free, at least asymptotically.

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1. – Life in Roma in the 1970s

In Roma, my wife Pucci and I used to see Guido Altarelli and Nicola Cabibbo out of work, with their wives and small kids. Sometime we would go to Fregene, in the nice seaside house of the Altarellis, or to Grottaferrata, in the country house of the Cabibbos, and to the lake of Bracciano with Pucci's family. We saw also other Roma professors, Giorgio Salvini, Marcello Conversi, Giorgio Careri and their families.

New younger people had joined, following Massimo Testa and Giorgio Parisi, who had started to collaborate with Nicola in 1969.

Keith Ellis, a young Italian speaking Scottish student, attracted to Roma by Preparata and recruited in our group by Guido, Roberto Petronzio, then a laureando of Nicola, and Guido Martinelli, also recruited by Guido. You will find their names appearing first in the literature in association with Nicola, with Guido and sometimes with me.

From time to time the Physics Department was occupied by the students, but we could find always a quiet office in Istituto Superiore di Sanità, across the road, where I worked. Roma and Italy were struck by social turmoil and terrorism, but our was a quiet, intellectually stimulating, academic life that I remember with pleasure and that never did come back.

I moved to the University La Sapienza as full professor in 1976 and Guido took the chair shortly after, in 1980.

With John Iliopoulos in Paris, very close relations were established between Roma and Phil Meyer's group in Orsay; Guido Altarelli and I were living in rue d'Ulm when, in 1974, the group moved from Orsay to École Normale Supérieure.

The discovery of the J/Ψ raised a lot of questions and we (Roma+Paris) offered to go to Utrecht to discuss the matter with Tini Veltman and Gerard 't Hooft, a meeting which became the annual Triangular Meeting Paris-Roma-Utrecht.

During my sabbatical leave in ENS, 1977-1978 (which followed Guido's), Giorgio Parisi came in and so did Nicola Cabibbo.

It was remarked, at that time, that Roma people saw CERN only from the airplane, flying to Paris...

2. – Roberto in Roma

A student of Nicola Cabibbo, Roberto started his career in theoretical physics in Roma in 1972. He was a bright, communicative, hard working student, who was able, immediately, to interact and work with us, in different configurations: with Nicola, of course, with myself and Guido Altarelli, then Keith Ellis, then Giorgio Parisi. These were exciting times, discoveries were coming almost every week from laboratories all over the world and the Roma group was very active in confronting the data with the predictions of the Standard Theory.

Roberto started with a work on neutrino interactions in a specific parton model that our group, including him, had developed at the time. It was the first time of Roberto in our group (1973) and he was to become soon a world recognised expert in electroweak deep inelastic interactions and QCD.

Our paper [2] was an attempt to reconcile the constituent quark and the parton pictures of the proton.

Proton was described in the $p \to \infty$ frame by three constituent quarks, according to the symmetry of the sixties: $SU(6)_W \otimes O(3)$ (which encompassed flavour, helicity and orbital angular momentum). It was further assumed that, in deep inelastic scattering, the virtual photon probes the structure of constituent u, d and s quarks, interacting with bare quark and gluon quanta (the partons). In this picture, proton's structure functions factorise in the constituent quark wave function times the structure function of the quark:

$$u(x) = \int_x^1 \frac{\mathrm{d}z}{z}\left[u_0(z)\phi_{uu}\left(\frac{x}{z}\right) + d_0(z)\phi_{du}\left(\frac{x}{z}\right)\right],$$
$$d(x) = \int_x^1 \frac{\mathrm{d}z}{z}\left[u_0(z)\phi_{ud}\left(\frac{x}{z}\right) + d_0(z)\phi_{dd}\left(\frac{x}{z}\right)\right].$$

The model gave a good description of deep inelastic scattering cross sections in terms of few parameters and it could be extended to meson structure functions without additional inputs and to other processes. We included the Drell-Yan process in meson-nucleon collisions and neutrino processes.

It somehow prepared the road to the Altarelli-Parisi picture to describe scaling violations that was to be developed few years later [3].

3. – At CERN

In the eighties our focus moved to CERN, where a Standard Theory group was blossoming, with John Ellis, Álvaro De Rújula, Mary K. Gaillard and others, and were Nicola and myself had been called to participate in Scientific Committees.

Fully developed as a mature scientist, Roberto was our reference person at CERN. The first occasion when I could see this, was the paper on the bounds to the Higgs mass in a Grand Unified Theory.

The renormalization group behavior of the Higgs self-interaction, $\lambda(q^2)$, is such that the t-quark Yukawa coupling (the t-quark mass) drives $\lambda(q^2)$ towards zero and then to negative values, that would make the theory unstable.

If this has not to happen before Grand Unification, the starting value of λ, say $\lambda(M_W^2)$, must be larger than some calculable number, function of M_t and of the cutoff $\Lambda \sim M_{GUT} \sim 10^{14}$ GeV, where λ becomes zero.

Since M_H^2 is proportional to $\lambda(M_W^2)$, a lower bound to M_H^2 is obtained.

We had discussed this with Nicola and Giorgio, had all the elements, but there had been no opportunity to make a real calculation.

While I was visiting CERN, Roberto took me in his office, put down the ingredients and we did compute the limits, see fig. 1. I think he also wrote a draft of the paper [4].

The one-loop limit to M_H has been refined with a two-loop calculation by Altarelli and Isidori [5] and by Sher [6]. After discovery of the Higgs with $M_H = 125$ GeV, the issue has been reanalysed at three-loops by Degrassi *et al.* [7].

4. – A world without the Planck mass?

Consider a gauge theory with one mass scale, $\mu \sim 170$ GeV for the Standard Theory. If the theory is ultraviolet divergent ($\beta(g) > 0$, unlike QCD at present energies) it can generate an exponentially larger mass scale, Λ,

$$\Lambda = \mu e^{+\frac{1}{bg^2}}, \tag{1}$$

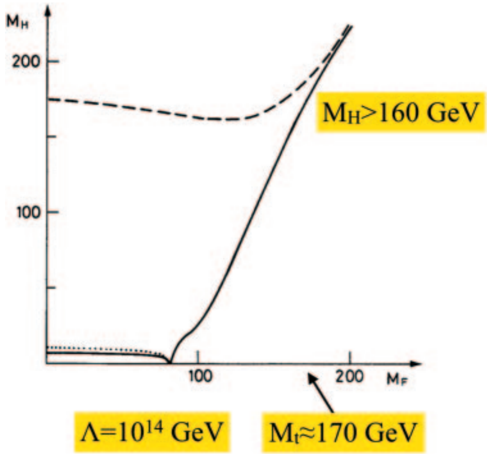

Fig. 1. – Allowed region in the plane of the heavy fermion (top quark) mass, M_t and of the Higgs boson mass, M_H, in the one-loop approximation. The lower bound to M_H, solid curve, arises from the condition that $\lambda(q^2) \geq 0$ for $q^2 \leq M_{GUT}$, see text. The upper bound, dashed curve, from the condition that a Landau pole does not develop before M_{GUT}. Figure from [4].

the position of the Landau pole where the gauge coupling diverges (b is the slope of the β-function).

In this case, strong interactions at Λ could produce strings, Regge poles,... even quantum gravity, perhaps. Also, if the Planck mass is generated in this way, there would be no hierarchy problem.

A situation like that was studied by Parisi, Petronzio and myself [8] with the result that: the interactions of $SU(3) \otimes SU(2) \otimes U(1)$ all diverge at $\Lambda = M_{Planck} \sim 10^{19}$ GeV for a number of quark and lepton generations $N = 8$.

What happens in the ultraviolet to the Standard Theory, that has $N = 3$?

- Colour and weak forces are asymptotically free and disappear at Λ;
- hypercharge forces diverge at

$$\Lambda = (170\,\text{GeV}) e^{(\cos^2\theta\ \frac{9\pi}{10N\alpha})} \sim 10^{44}\,\text{GeV},$$
$$\text{for } N = 3$$

($\cos\theta$ is the Glashow-Weinberg-Salam angle).

New fermions are evidently needed, with the risk however that:

- if coupled to the Higgs boson, the new fermions will drive the Higgs coupling to negative values, well before Λ;
- if vector-like, they introduce new masses, which are potential sources of new hierarchy problems.

Paradoxically, as found by Cabibbo and Farrar [9], the best compromise seems to have $N = 5$ supersymmetric generations, which would diverge at M_{Planck} and not drive the Higgs coupling to instability (in SUSY, the Higgs self-coupling is proportional to g^2 and it cannot become negative).

5. – Further works (many more to be illustrated by the other speakers)

At CERN, Roberto got interested in the numerical, non-perturbative simulation of QCD with Monte Carlo methods.

With Nicola Cabibbo and Guido Martinelli, in 1984, he made a pioneering work on the calculation of the QCD renormalisation of four-fermion operators [10]. The paper opened a new road to compute the non-perturbative renormalisation of weak-interaction matrix elements (B-factors), which was to have an important impact on the determination of the Cabibbo-Kobayashi-Maskawa matrix, providing a crucial test of the Standard Theory.

After a seminar by Zavattini on PVLAS, we worked out axion-photon oscillations in a strong magnetic field and the possible generation of a new kind of vacuum birifrangence in photon's propagation (an effect still searched for in the PVLAS experiment) [11].

With Cabibbo and Parisi, Roberto has been a leading figure of the APE project (Array Processor Experiment) aiming at design and construction of a highly performant, highly parallel processor optimized for QCD calculations [12].

After CERN, Roberto was visiting professor in Ècole Normale Superièure, Paris, Max Planck Institute, Munich, and Boston University. In Munich, he made the interesting proposal to test the formation of a plasma of unconfined quarks and gluons by the suppression of J/Ψ production [13], which received much experimental attention.

6. – A science manager

Roberto has been a much appreciated science manager and, as INFN President (2004-2011), he mastered a difficult period of reformation of the Italian Research Institutions.

While increasing transparency and accountability of the organisation, Roberto succeeded to maintain independence, autonomy and form of governance of INFN, that have been at the basis of the indisputable success of this Institution.

As Chair of the Steering Committee of ICTP, he guaranteed an efficient connection between ICTP and the Italian Government. He brought ICTP and INFN closer together and strengthened the existing links between the two institutions, promoting a very successful collaborative agreement between ICTP and INFN.

After 2011, I used to meet him in Trieste, on the occasion of the ICTP Scientific Council, and could appreciate his understanding of administrative and political problems and his ability to find clever solutions.

Sometime, we had dinner in the small harbour of Grignano, where I enjoyed our relaxed conversation on his plans for a new accelerator and on the way research could be done, in Italy and abroad.

The expansive, ambitious student I met in the seventies had acquired confidence, wisdom and vision.

7. – A farewell

Roberto has been a first-class scientist who was able to work on all fronts of modern theoretical physics. He was creative, hard worker and he liked to share with others his enthusiasm for research and to work in team.

A fine mathematical mind, Roberto never lost sight of the relationship that goes between theory and experiment and was able to suggest meaningful experiments himself, devised to test delicate aspects of the theory. For this, he was widely appreciated and respected.

Towards the end of his INFN mandate, Roberto launched the ambitious program to build in Italy, with an international venture, an advanced accelerator to study the decay of B-mesons and the physics of flavour.

For lack of resources, the original project of a very high-luminosity B-factory near Tor Vergata had to be scaled down to a charm-tau factory. It was this project that Roberto was working at when, in 2014, he was caught by a stroke that left him confined in bed, in very severe conditions, until his untimely end.

Unfortunately, even the reduced project has been abandoned and it is now to the Italian particle physics community to take the challenge of a tradition which started with Enrico Fermi and continued with Bruno Touschek, Raoul Gatto, Nicola Cabibbo and so many others, Roberto Petronzio included.

We sorely miss him.

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