Chapter 7
The Standard Theory and Theoretical Physics in Roma

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Abstract After a brief description of the rise of the Constituent Quark Model for hadrons, I illustrate the contributions of the Roman Theoretical School to the formation and exploration of the Standard Theory of fundamental particles, in the years 1970 to 1990.

7.1 Introduction

In 1937, C. Anderson and S. Neddermeyer discovered a new particle produced in the upper atmosphere by the collisions of Cosmic Rays. In 1946, in Roma, M. Conversi, E. Pancini and O. Piccioni proved that the mesotron (μ particle, today) is not the particle responsible for the nuclear forces, proposed by H. Yukawa. Many consider this discovery to be the birth of modern Elementary Particle physics.

Everybody (Fermi, Marshak, etc.) was worried: where is the pion?

Pontecorvo asked an apparently simpler question: what is the mesotron? and proposed a surprising answer: it is a second generation electron. I. Rabi commented: who ordered that?

What is the role of μ particle in the fundamental forces? A provisional answer was the concept of Universality of the Weak Interactions (Puppi, 1950). This line of research, after Feynman and Gell-Mann, Marshak and coll. and, later, Cabibbo, led eventually to electroweak unification (Glashow, Weinberg, Salam, Higgs and Englert). But we still do not have a plausible explanation of why are there different generations.

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7.2 Elementary Constituents Versus Nuclear Democracy

In 1940–1950, a particle zoo emerged from the study of cosmic ray interactions.

The new particles do not arise from further subdivision of normal matter (atoms, nuclei, nucleons, atomic and nuclear forces) and *the probability that all such particles should be really elementary becomes less and less as their number increases* (Fermi and Yang [1]). The proposal by Fermi and Yang was that not all the observed particles are elementary. They proposed the Yukawa particles, the pions, to be nucleon-antinucleon bound states, e.g. $\pi^+ = (p\bar{n})$. The natural symmetry of the Fermi–Yang scheme was the Isospin symmetry displayed by the nucleon doublet, the $SU(2)$ symmetry, which propagates to their mesonic bound states, as indeed is observed.

The only, but very startling consequence one could derive from the Fermi–Yang hypothesis was that the pion has to have a negative parity, as indeed was indicated in these years by pion photo-production experiments.

With the discovery of the strange particles, in 1956 Sakata [2] proposed the Λ baryon as the additional elementary constituent

$$\begin{aligned} &\text{elementary} : S = (p, n, \Lambda) \\ &\text{mesons} = S\bar{S}; \quad \text{baryons} = SS\bar{S} \end{aligned} \tag{7.1}$$

The natural symmetry was now promoted from $SU(2)$ to the unitary transformations in a three-dimensional complex space, $SU(3)$. The Sakata model reproduces well the meson spectrum, and it makes a clear prediction: there must exist baryons with strangeness $S = +1$. Unfortunately it is a wrong prediction, no such particle has been seen until today!

On a different line of thinking, one can argue that, in the presence of very strong (unitarity saturated) interactions and using crossing symmetry, there is no clear distinction between composites and constituents:

$$\pi^+ = p\bar{n}, \text{ or rather } n = \bar{p}\pi^+ \text{ ???} \tag{7.2}$$

The most natural principle to start with, in the Sixties, was considered to be **Nuclear Democracy**: all strongly interacting particles, collectively called *hadrons*, are to be treated on the same footing (G. Chew and S. Frautschi).

It was also believed that unitarity and maximal analyticity of scattering amplitudes could provide the dynamical equations needed to determine the hadron spectrum. Recalling the story of the Baron of Munchausen, this approach received the suggestive name of *bootstrap*: to lift up himself by pulling the boots of his own shoes (or his pigtail as the Baron did to get out of the swamp).

Nuclear Democray and bootstrap had no real, recognized success. However, these principles inspired the dual model of Gabriele Veneziano, which, later, gave rise to *String Theory*, the basis of many theories of Quantum Gravity.

For sub-nuclear particles, the meaning of constituents was understood only in 1973.

Nuclear democracy holds. Subnuclear particles are on the same footing: they are all composite and the elementary constituents are quarks and gluons, endowed with a new quantum number, colour

$$\text{elementary} : q = (u, d, s),\ gluons \leftrightarrow \text{generators of the colour group } SU(3).$$

and, after Gell-Mann [3] and Zweig [4]:

$$\begin{aligned} \text{mesons} &= q\bar{q},\ qq\bar{q}\bar{q},\ \ldots \\ \text{baryons} &= qqq,\ qqqq\bar{q}, \ldots \end{aligned} \tag{7.3}$$

The fundamental strong interaction is the gauge theory associated to colour, Quantum Chromo Dynamics. It becomes weak at short distance, as shown by Gross and Wilczek [5] and by Politzer [6], so as to allow the unambiguous identification of the constituents.

7.3 Gatto, Cabibbo, Touschek and Cini in Roma and Frascati

In 1951, after the Diploma at Scuola Normale di Pisa, Raoul Gatto went to Roma as assistant to Bruno Ferretti.

In 1956, he left for the United States, to become a staff member of the Lawrence Radiation Laboratory in Berkley. The group of Luis Alvarez was in full production, discovering new hadrons with the hydrogen bubble chamber. Gatto absorbed quickly the exciting atmosphere of the laboratory. In close contact with the Alvarez group, he produced works on the symmetries of the weak interactions (Fermi's imprint on Italian theoretical physics) and the phenomenology of weak decays of hyperons.

Coming back in 1960, Gatto became the director of the newly formed theory group at Frascati, bringing to Italy the new ideas flourishing at the time in the US, concerning the application of symmetry and group theory to particle physics. He found, as junior partner, Nicola Cabibbo.

Nicola had graduated in 1958, tutor Bruno Touschek, and was the first theoretical physicist hired in Frascati by Giorgio Salvini, then director of the Laboratory.

These were exciting times in Frascati. Touschek and collaborators were building the first collider (AdA), to be followed by Adone (1969), a new particle (the eta meson) was discovered, checking the freshly introduced SU(3) symmetry.

Cabibbo and Gatto authored an important article on e^+e^- physics in 1961, promptly named *the Bible*. Among other works, they investigated the weak interactions of hadrons in the framework of the SU(3) symmetry (a precursor of Cabibbo theory of the weak interaction angle [7], made at CERN two years later).

Brilliant younger collaborators joined in Frascati: G. Da Prato, U. Mosco, G. De Franceschi and, later, G. Altarelli and F. Buccella (graduated with Gatto), G.

Gallavotti (with Touschek). The preparation of ADONE experiments prompted the renewal of QED studies.

In year 1962–63, Touschek was teaching Statistical Mechanics in Roma. He would present his lecture consulting personal notes that he had probably prepared the night before. In the presentation, it seemed as if he had just discovered what he was explaining.

Extremely clear and precise, Touschek spoke a perfect Italian with a fascinating Austrian accent and sometime old fashioned expressions. He referred to the heat bath to reach thermal equilibrium as "vasca di bagno" and described his revolutionary idea of making head-on electron-positron collisions as "treno-contro-treno". One could see the perfect image of a scientist and a perfect illustration of how rewarding research in physics might be.

Most importantly, in Roma Touschek kept alive the interest in field theory, given as dead in most countries, actively cultivating the study of QED, Fermi theory and of fundamental symmetries (Majorana and the two components neutrino theory).

During the late Fifties and early Sixties, theoretical alternatives to field theory were explored in Roma by Marcello Cini, with many young collaborators. Among them, M. Cassandro, L. Sertorio, M. Restignoli and, later L. Violini, M. Lusignoli, M. Toller, D. De Maria. Subjects went from the Fundamentals of Quantum Mechanics to Dispersion Relations, Regge Poles, Relativistic Thermodynamics.

7.4 Particle Physics in the Late Sixties

Hopes to reach a basic theory for strong, e.m. and weak interactions flourished in the late Sixties, based on several important results obtained in the first part of the decade

- quarks in three flavours, introduced by M. Gell-Mann and George Zweig, gave an excellent explanation of the observed meson and baryon spectrum;
- the Cabibbo theory of semileptonic $\Delta S = 0, 1$, hadron decays, marked a substantial progress with respect to the Fermi theory, enlarging universality to strange particle decays, via $d - s$ quark mixing.

There were clouds as well, indicating that something was still missing

- the clash with Fermi statistics of quarks in the baryon wave functions, with the first ideas about colour by Han and Nambu [8];
- the unexplored form of quark strong interactions inside hadrons; the exchange of an abelian gluon was often used as a toy model;
- The Fermi interaction was known to be non-renormalizable. Could W boson intermediary help?

Schwinger ideas about Yang-Mills theory and ElectroWeak unifications had been substantiated by Glashow [9] in 1961, with the introduction of the $SU(2)_L \otimes U(1)_R$

gauge group, with interactions mediated by the photon and by the massive intermediate bosons $W^{\pm}$, Z. The Brout–Englert–Higgs Mechanism had been worked out in 1965, leading to the Weinberg-Salam electroweak theory for leptons [10], in 1967.

It was known that embedding Cabibbo theory with three quarks in $SU(2)_L \otimes U(1)_R$ led to unobserved Flavor Changing Neutral Currents. Open questions: does Unification work for leptons only? may form factors suppress these processes?

In the late Sixties, few people believed that the basic strong interactions between quarks could be described by field theory. In the more established framework, Bootstrap, Regge Poles etc., a very promising new idea came out, the Dolen–Horn–Schmid Duality [11]: *the sum of baryon, s-channel resonance amplitudes reconstructs the (is dual to) Regge behavior in the t-channel and vice-versa.*

Duality was a new kind of bootstrap condition, and the result raised a lot of interest, which reached its maximum in september 1968 when Veneziano proposed a Dual Model of pion-pion scattering [12]. *Everybody went Dual.* Field theory for particle physics became an exoteric discipline, with few practitioners worldwide.

Nonetheless, few authors addressed the problem of higher order weak interactions in a bottom-up fashion, using the simplest theory with one charged vector boson coupled to the Cabibbo currents. At one-loop level, they found a startling, unexpected result [13–16]. The Vienna HEP Conference, August-September 1968, marked the real turning point.

Ideas about Duality were presented and widely discussed. Higher order weak interaction results about flavour changing neutral currents were presented and discussed (Cabibbo was the convenor of the weak interaction session). SLAC data on deep inelastic electron scattering were presented for the first time, indicating the onset of Bjorken scaling.

7.5 The First Weak Interaction Loop

At one loop, with one charged vector boson coupled *à la* Cabibbo, $K_L \to \mu^+\mu^-$ and $K^0\bar{K}^0$ mixing are generated, with amplitudes of order: $\sin\theta\cos\theta\ G(G\Lambda^2)$, where G is the Fermi constant and Λ an ultraviolet cutoff.

The strict experimental limits existing at the time implied the surprisingly small value: $\Lambda \sim 2-3$ GeV, to be compared with the naturally expected value: $\Lambda = G^{-1/2} \sim 300$ GeV. The result was obtained by using current algebra commutators and showed that the ultraviolet divergence, in the theory with three quark flavours, *is not damped* by form factors, as a consequence of the intrinsically point-like, current algebra commutators.

The result eventually[1] led, in 1970, to the GIM Mechanism [18]: the introduction of a charm quark to cancel the quadratic divergence and the related interpretation of the Ioffe–Shabalin cutoff as a prediction of the charm quark mass, $m_c \sim 1.5$ GeV.

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[1] The road to the GIM mechanism is described in [17].

GIM gives the possibility to include quarks in the Glashow-Weinberg-Salam gauge theory based on $SU(2)_L \otimes U(1)_R$. It was the first instance in which quark and W loops were taken seriously and led to startling predictions that indeed have been verified a few years later.

By the end of January 1970, in Harvard I think we had understood all the essentials. I remember one day going to the Legal Sea Food restaurant for lunch, where my wife Pucci joined us. Pucci told Shelly (Glashow) how happy I was about the new result and the work we were doing. He replied: *He is right, this paper is going to be in all school books*. Shelly was fantastic. In another occasion, a seminar given by him to the experimentalists of Harvard working at the CEA (Cambridge Electron Accelerator), Shelly introduced his talk by saying: *Look, with charm we have essentially solved particle physics*. *Except*, he added, *for CP violation*. Something that had to be reconsidered three years later by Makoto Kobayashi and Toshihide Maskawa [19], with the introduction of a third generation.

7.6 May 1970: Back in Roma

ADONE started operating at the end of 1969 and produced its first results in 1970.

All detectors observed an unexpected abundant production of hadrons. Beyond the ρ, ω, ϕ and ρ' resonances, the ratio of the hadronic to the $\mu^+\mu^-$ cross section was nearly constant and of order unity, as if the process went via the production of point-like constituents.

Coming back to Roma from the US, in may 1970, I found Nicola Cabibbo and his present and former students (Giorgio Parisi and Massimo Testa) very excited by the ADONE results. Needless to say, Touschek was greatly excited as well: the unexpected result indicated the crucial importance of e^+e^- collisions to investigate the deep structure of matter. In analogy with the formulae found by Drell and Yan for deep-inelastic muon pair production, they were playing with the formula [20]

$$R = \frac{\sigma(h)}{\sigma(\mu^+\mu^-)} = \frac{1}{4}\sum (Q_i^0)^2 + \sum (Q_i^{1/2})^2 \qquad (7.4)$$

with $Q_i^{0,1/2}$ the electric charge of elementary constituents with spin 0 or 1/2. But: which constituents? Cabibbo, Parisi and Testa made different hypotheses, including spin 0 constituents, but it was only with more precise data that a definite conclusion has been possible.

Figure 7.1 gives a recent picture of the experimental determination of R [21]. The virtual photon created by the e^+e^- annihilation is a universal probe for any form of electrically charged matter. Different hypotheses about the quarks present in the final state give the values:

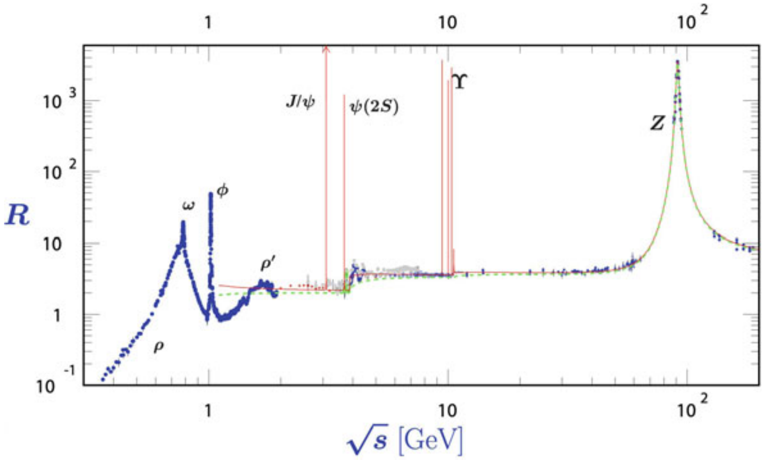

Fig. 7.1 The ratio R, (7.4), in the energy regions of Adone, SLAC and LEP. Particle Data Group [21], courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, May 2010

$$
\begin{aligned}
R &= \\
&= 2/3 \text{ (u, d, s, no colour)} \\
&= 2 \text{ (u, d, s, each in 3 colours)} \\
&= 2 + 4/3 \text{ (u, d, s, c in 3 colours)} \\
&= 5 \text{ (three generations in 3 colours)}
\end{aligned}
\qquad (7.5)
$$

In 1972, Gell-Mann was visiting CERN. In May he participated in a Conference in Frascati organised by Gatto. In a talk to the conference, Gell-Mann reported about work done with Bardeen and Fritzsch, where the idea of QCD was proposed [22, 23], based on a colour gauge group commuting with the electroweak group. This was before the discovery of Asymptotic Freedom of non-abelian gauge theories [5, 6].

In that occasion, Gell-Mann visited our Department in Roma and gave a seminar on QCD. He remarked that the hypothesis of fractionally charged quarks with three flavours and three colours gives $R = 2$. Conversi, present in the seminar, stated that the value observed by Adone was in fact converging to a ratio ~ 2, see Fig. 7.1.

After the J/Ψ peak, the ratio has a small increase, consistent with the $+4/3$ difference expected for the additional production of charm quark pairs. The association of J/Ψ with the $c\bar{c}$ threshold was first done in [24].

At even higher energies, $Y = b\bar{b}$ resonances appear, associated to a much smaller increase $\Delta R \sim +1/3$, corresponding to the creation of b-quark pairs. The very large Z^0 peak appears in the LEP region, associated with the neutral intermediary of the weak interactions. A further increase is expected, but not yet observed, after the $t\bar{t}$ threshold, where R should saturate the three-generation level, $R = 5$.

No signal of further structures, associated with new kinds of constituents or intermediary vector bosons has been observed so far in the single, virtual photon channel. It is left to future electron-positron, circular or linear colliders [25] to explore the region above the $t\bar{t}$ threshold, in search of further constituent matter.

7.7 Going Electroweak

Guido Altarelli was back in Roma in 1970, as Assistant Professor.[2] In 1971, Veltman and ’t-Hooft proved that the Weinberg Salam theory is renormalizable: *everybody became electroweak.*

Guido and I began discussing with Nicola how to compute Electroweak corrections to the muon $g-2$, due to the exchange of vector bosons and the Higgs boson. It was a new territory, at least for us, a lot of calculations and a lot of fun. Also many difficulties with inconsistent calculations: we called it *the rebellion of the matrices!* but we got it [26], at about the same time as other distinguished people [27].

The Adler, Bell–Jackiw anomalies in $SU(2)_L \otimes U(1)_R$ were the last obstacle towards a renormalizable electroweak theory.

Anomalies affect both quark and lepton currents. Bouchiat, Iliopoulos and Meyer [28] worked out the conditions for a cancellation to be operative. John’s description of this work, in a short letter he sent me, was: *there must be charm, quarks have color and are fractionally charged.*

Asymptotic Freedom in QCD was found shortly after [5, 6]: the era of the Standard Theory had started.

7.8 Working in Roma in the Seventies

In Roma, Pucci and I used to see Guido and Nicola out of work, with wives and small kids.

Sometime we would go to Fregene, in the nice seaside house of the Altarellis, and to Grottaferrata, in the country house of the Cabibbos. We saw also other Roma professors, Salvini, Conversi, Bernardini, Careri and families.

New younger people joined in: Massimo Testa, Giorgio Parisi, Keith Ellis (a young Scottish, Italian-speaking student, attracted to Roma by Preparata and recruited in our group by Guido), Roberto Petronzio and, later, Guido Martinelli (also recruited by Guido). You will find their names appearing in the literature at first in association with Nicola, with Guido and sometimes with me.

From time to time the Physics Department was occupied by students, but we could always find a quiet office in Istituto Superiore di Sanità, across the road, where I worked. Roma and Italy were hit by social turmoil and terrorism, but our was a

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[2] This and the following Sections are taken almost literally from [17].

quiet, intellectually stimulating, academic life that I remember with pleasure and that did not come back.

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

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

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

Guido took a crucial sabbatical in ENS in 1976–1977. Later, Giorgio Parisi came in and so Nicola Cabibbo, during my sabbatical in ENS, 1977–1978. It was remarked, at that time, that Roma people saw CERN only from the airplane, flying to Paris …and we all lived under the surveillance of Claude Bouchiat and the quiet but firm protection of Philippe Meyer.

7.9 The Altarelli–Parisi Equations

J. Iliopoulos, in his Plenary Report at ICHEP London, 1974, speaking about Asymptotic Freedom, observed [29]

as it is often the case, whenever someone talks about freedom, it invariably turns out that he really means something else. The same is true here.

Quarks are not really free in deep inelastic reactions. Deviations from exact Bjorken-Feynman scaling must be expected. Asymptotic freedom in QCD makes them calculable.

Parisi was after scaling violations very early, but all seemed very complicated and unintuitive. Then came the paper by Altarelli and Parisi [30], 1977, with a similar contribution from Dokshitzer [31] in the same year, anticipated by Gribov and Lipatov [32] in 1972: this became known as DGLAP.

The AP paper has had an enormous impact, it made easier to understand the physics and simpler to compare experimental data with theory. Guido was amused to see that their paper was rated at that time as the most quoted French theoretical paper in particle physics.

7.10 New Research Lines and New Younger Generations in Roma

Few results obtained in Roma during the wonderful years from 1974 to 1991 opened new research lines in the Standard Theory. They also saw the emergence of new generations of theorists. A, possibly incomplete, list goes as follows

- Enhancement of non-leptonic weak interactions due to QCD renormalization effects [33];
- Calculations of parton densities in the hadrons [34]
- Parton calculations of the electron beta decay spectrum of heavy quarks [35].
- QCD prediction of a phase transition from hadrons into deconfined quarks and gluons [36]
- Bounds to the Higgs boson and heavy fermion masses in grand unified theories [37]
- Lattice QCD calculation of weak parameters with lattice QCD [38].
- Proposal and realisation of the APE parallel supercomputer for lattice QCD calculations [39].
- Lattice QCD calculation of the decay constants of pseudoscalar charmed mesons, f_D and f_{D_s}, and beauty mesons, f_B [40].

7.11 Conclusions

The discovery of W [41] and Z [42] in 1983 concluded the heroic phase of the Standard Theory. Since then, up to the observation of the Higgs Boson in 2012 [43], we have had only confirmations.

The Standard Theory may not be the final word. There are many hypotheses advanced, only future experiments will tell what is really beyond ST.

Field theory has come back: will it be superseded by more subtle concepts? supersymmetry? strings?

Touschek idea of colliders has been essential for discovery and verification of the Standard Theory and it plays now a fundamental role in particle physics.

Our generation has been very lucky to be there, at the right place and the right time, and it all has been, indeed, a great fun.

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