

Chapter 6

Adone, Asymptotic Freedom and QCD



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Abstract I am collecting some personal remembrances of the construction of the Adone intersecting storage ring and of the very first years of operations. I will discuss mainly particle theory at the beginning of the sixties and its impact on the design of experimental apparatus and the contribution of Adone to the emergence of QCD.

6.1 Introduction

This chapter is mainly based on personal remembrances. I started to be interested in Adone physics in 1970 [1] and I was a researcher in the Frascati National Laboratories starting from January 1971 for 10 years. The construction of the Adone was quite a recent effort and the exploitation of the machine was just starting, I have been a witness to those events: this paper can be considered mostly a primary historical source.

In this chapter, I discuss in sequence the following arguments.

- The Adone intersecting storage ring.
- Particle theory at the beginning of the sixties.
- The impact of the theory on the design of experimental apparatus.
- Partons: back to field theory.
- A new paradigm: QCD, Asymptotic freedom and quark confinement.

Contrary to many other speakers I had not too many interactions with Bruno Touschek. For various reasons (that at the time I had not fully investigated) Bruno was not coming too often to Frascati. I remember some discussions of physics with him at the University. A particular episode stuck in my mind.

Around 1971 a preprint arrived where it was claimed that the cross-section for the process

$$e^+e^- \rightarrow 2e^+2e^- \quad (6.1)$$

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was of order $1/m_e^2$ and not $1/E^2$ as expected. The difference in the prefactor produces an enhancement of the order 10^6 . It was very clear to Nicola Cabibbo that the paper was wrong. A factor $1/m_e^2$ is present in individual Feynman diagrams, but it cancels out if you sum different diagrams without doing algebraic mistakes. If you do the right computation, you find an enhancement factor of only $\log(E/m_e)^2$. I remember that I and someone else were in Nicola's room where Nicola was presenting his ideas on the subject showing that one can do a simple *Blitz* computation.¹ Bruno entered in the room and he started the conversation by immediately declaring: *I do not understand how a grown-up man can write such a nonsense*. He was right!

Of course, at Frascati, there were many circulating anecdotes about him. In the summertime after lunch, he was going to the nearby lake of Castel Gandolfo for the *tocca tinca*, i.e. while snorkeling, trying to touch the tail of a “tinca” (a tench, a freshwater fish); he also asked friends to come with him claiming that this was a very good occupation for theoretical physics. But without too much success.

In this talk, I will also not cover in detail the Physics at Frascati with AdA and Adone that is the subject of Mario Greco's talk in these *Proceedings*.

6.2 The Adone Intersecting Storage Ring

The idea of constructing an e^+e^- intersecting storage ring was presented in a historical seminar at Frascati in March 1960. After the seminar things moved quite fast. In the proceedings of a conference held at CERN in June 1961 [5] Touschek describes the situation at the beginning of his contribution (Fig. 6.1).

Frascati is developing two storage rings. The first (code name AdA = anello d'accumulazione = storage ring) designed for storing electrons and positrons of up to 250 MeV is actually undergoing the first tests, the second (code name Adone) a storage ring for electrons and positrons of up to 1.5 GeV, is still being planned.

The AdA team consists of C. Bernardini, G. F. Corazza, G. Ghigo, B. Querzoli and myself. The magnet was planned by Dr. Sacerdoti and built in Terni, the radiofrequency by Dr. Puglisi.

Adone is a national effort. A design team headed by Dr. Amman has the task of arriving at a specific design proposal by the beginning of 1962. Simultaneously a committee is preparing the experiments to be carried out with the machine. If by the beginning of 1962 it is found that the project has a reasonable chance of success from a technical viewpoint, it is expected that the machine should be working in late 1964.

Let me be very brief on the Adone project: electrons and positrons circulate in a magnetic ring designed to contain particles up to 1.5 GeV energy. The energy losses

¹ This episode was important in a historical perspective. Nicola's computations were published much later in a joint preprint with Rocca. They computed the probability of finding inside a γ a triplet γ, e^+, e^- [2]. I had many discussions with Nicola on these generalized Weizsäcker–Williams relations and his work had deeply influenced my paper with Guido Altarelli on *Altarelli Parisi equations* [3].

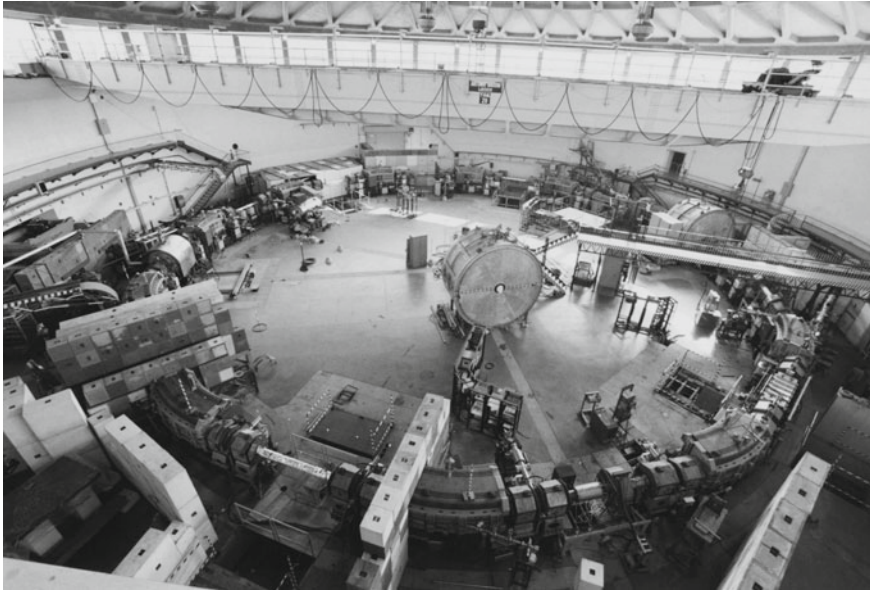


Fig. 6.1 A photograph of the Adone Intersecting ring with the experimental apparatus. Copyright INFN—LNF

are replaced by R.F. Injection is effected by means of a low energy (of between 50 and 200 MeV). The final energy is reached by raising the magnetic field to the desired value.

AdA was a great success [4]. After the first positive results the construction of Adone started immediately and in 1968 Adone was completed [6, 7]: the beams of electrons and positrons circulated in a ring 105 m long, divided into 12 equal sectors composed of a bending dipole, followed by a pair of quadrupoles and a straight section of 2.5 m.

Four of the 12 straight sections available allowed the intersection of the beams, resulting in many points of interaction for the installation of the experimental equipment. Four experimental apparatus have been constructed. The remaining 8 sections housed the radiofrequency cavities and the equipment for beam injection and diagnostics.

The maximum project energy of Adone was 1.5 GeV per beam, but after November 1974 it operated also at 1.55 GeV. The minimum energy was around 0.7 GeV.

I remember that someone told me that during the construction of Adone, Bruno and the others had to take irreversible decisions without no hints. In all the cases the decisions were the right ones, otherwise, Adone could have had years of delay. This was a nice example of serendipity. The project was not perfect and there were some unforeseen phenomena: fortunately in all the cases the cure, often found by Bruno, was not too complex.

6.3 Particle Theory in the Beginning of the Sixties and the Design of the Experimental Apparatus

Around 1960 Geoffrey Chew proposed the *bootstrap* philosophy [8]. There were no elementary constituents, all particles were supposed to be on the same footing. This approach became extremely popular and also Murray Gell-Mann was not taking quarks seriously: he considered them as a mathematical model to implement $SU(3)$ symmetry. Field theory was discredited and some authors suggested that a good knowledge of quantum field theory was detrimental to the comprehension of bootstrap. This was a somewhat strange position because dispersion relations were a cornerstone of bootstrap and they were firstly derived in the context of local field theory. Ironically the bootstrap approach was instrumental to the birth of string theories that are among the most sophisticated quantum field theories.

The absence of elementary point-like objects was suggesting that hadrons were extremely soft. This viewpoint was confirmed by the very fast decay of the proton form factor, by the exponential suppression of particle productions at large momentum transfer, and by Hagedorn theory where a maximum temperature somewhat less than 200 MeV was supposed to be present in nature: also a very energetic hadronic fireball would emit hadrons of no more than few hundredth MeV.

There was also a different viewpoint: electromagnetism, Fermi interactions, and the V-A theories for weak interaction were based on local currents and quantum field theory. The purely leptonic electro-weak was described by a field theory that was non-renormalizable, however, there was some hope that the introduction of heavy vector Bosons could make the theory renormalizable.

The semi-leptonic weak interactions were mediated by a hadronic current, and the resulting current algebra (based on local commutators) was crucial to normalizing the weak interaction vertices, which played a fundamental role in Cabibbo's theory of weak interaction. This quantum field theory approach to physics was strongly pushed in Europe: there were strong collaborations among different scientific institutions that were later formalized in the Triangular Meetings (Paris-Rome-Utrecht). The impact of the theory on the design of experimental apparatus was obviously strong. The bootstrap approach was the most popular and the alternative approach based on quantum field theory was not mature to propose a credible alternative.

There was a widespread belief that the dominant process should be the production of 2 particles (like $\pi^+ + \pi^-$) or 3 particles (like $\pi^+ + \pi^- + \pi^0$). The cross section was supposed to be small at energies greater than 1 GeV in the center of mass: indeed the 2 body processes (and in a similar way the three body processes) were controlled by form factors that were known to decrease very fast (at least in the case of the proton) at large momentum transfer (q^2).

Most of the interesting physics was supposed to be the discovery of new resonances like ρ' , or of exotic objects like a heavy electron (τ in modern language) that unfortunately had slightly too high energy to be observed at Adone.²

Consequently, the four experimental apparatus had a small fraction of solid angle that was enough for collinear and planar events: in these cases, the distribution of the produced particles was easy to predict. For two-body collinear events the angular dependence is well known. For three-body events one has to study the Dalitz plot of the events: this is a relatively simple job as far as the Dalitz plot could be easily parametrized in terms of a few parameters.

6.4 Partons: Back to Field Theory

6.4.1 Partons in Electron Collisions

In 1968 experiments at SLAC show a large cross section for the process (deep inelastic scattering)

$$e^+ + \text{proton} \rightarrow e^+ + \text{hadrons.} \quad (6.2)$$

Bjorken shows that these large cross sections are consequences of current algebra sum rules. Feynman introduces the idea of partons (field theory under disguised form) suggesting that these events were the signature of the presence of hard, point-like components inside the hadrons.

Adone started to work in 1969 and from 1970 it was clear that the total hadron production was quite high, more than the $\mu^+\mu^-$ cross sections and many events had a charged multiplicity greater than 2 (multi prong events). It was a mess to be sure of the value of the cross section for hadron production as far as the efficiency for detection depends on the production model. After some time it became clear that the ratio

$$R = \frac{e^+e^- \rightarrow \text{hadrons}}{e^+e^- \rightarrow \mu^+\mu^-} \quad (6.3)$$

was around 2 without a great dependence on the energy [9–11, 18].

In 1970 Nicola Cabibbo, Massimo Testa, and I derived the formula

$$R = \frac{e^+e^- \rightarrow \text{hadrons}}{e^+e^- \rightarrow \mu^+\mu^-} = \sum_i Q_i^2 + \frac{1}{4} \sum_i B_i^2, \quad (6.4)$$

² I remember that around 1972 I was discussing with Luciano Maiani about the signature of charmed mesons or heavy electrons and we noticed that direct production of $e - \mu$ and hadrons would be present in both cases, so we could not discriminate directly the two cases and some confusion could arise if the two channels would open at similar energy. After some reflections, we concluded that it was extremely unlikely that the threshold should be similar. Amazingly the lowest mass of a charmed charged meson is 1870 MeV and the mass of the τ 1777 MeV.

where Q_i are the charges of the spin 1/2 partons and B_i are the charges of the spin 0 partons. In the naive quark model

$$R = \frac{2}{3} \quad (6.5)$$

For partons that are $SU(3) \times SU(3)$ mesons $R = 1$.

Around 1971 Fritzsch, Gell-Mann, and Leutwyler suggested that the correct theory is given by colored quarks interacting via an octet of colored gluons. I remember a seminar given by Gell-Mann (1972) in “Aula Fisica Superiore”,³ where Gell-Mann proposed QCD. During that seminar, he said that in QCD

$$R = 2 = 3 \frac{2}{3}, \quad (6.6)$$

where the extra factor 3 comes from the color of quarks.

After the seminar Conversi remarked that this was in agreement with Frascati data. Gell-Mann was quite impressed.

6.4.2 Asymptotic Freedom

Landau noticed in 1955 that all known renormalizable theories had a divergent effective coupling at high energy, but for gauge Yang–Mills theory the computation was not done. Around 1966 the Russian physicist Iosif Benzionovich Khriplovich [15, 16] computed the beta function for Yang–Mills theory in a very elegant way: I do remember the argument very well.⁴ The paper started to be quoted after 1977, unfortunately it did not affect history, most of the citations started nearly ten years later. I noticed it at the end of the seventies looking for something else on.

In 1972 things started to move fast: Symanzik noticed that the $g\phi^4$ theory is asymptotically free for negative g : in this way, one obtains a *field theory with computable large-momenta behaviour*.

In the same year t’Hooft presented at the Marseille conference his result on the negative sign of the beta function for small coupling constant in Yang–Mills theory (a five-minute remark) that received not much attention apart from Symanzik: no preprint or paper was ever written.

³ The classroom is currently dedicated to Marcello Conversi at the Physics Department of Sapienza University in Rome.

⁴ The idea was to compute the logarithmic shift in the vacuum energy in presence of a constant magnetic field. In electrodynamics the computation was done by Heisenberg and Euler in 1936 [17]. In general there are two contributions that are well known for electromagnetism: the effects of Landau levels for free electron of the sea and the polarization of the corresponding spins. Generalizing these results to particles of spin 1, it was very simple to get the results without doing a loop computation.

In 1973 Politzer and Gross & Wilczek computed the beta function, and published their results showing that QCD is asymptotically free. This opened the way to a detailed comparison of the theory with experiments. At the end of 1973, I presented the first evaluation of the running coupling constant from violations of Bjorken scaling, so it was possible to start to compare the theory with experiments.

In 1974 the discovery of J/ψ at Brookhaven and SLAC, immediately reconfirmed at Frascati proved the existence of charm. The value of the widths of the ψ particle in hadrons or $\mu^+\mu^-$ were measured both at SLAC and Adone: They were in good agreement with the theoretical prediction using the charmonium model and provided an independent estimate of the running strong coupling constant.

The success of the charmonium model was undisputed when the first excited state was found at SLAC (ψ') and its pseudo scalar partner η_c was found at DESY. The same model gave good predictions for the mass splitting $\psi - \eta_c$, for the width for the process $\psi \rightarrow \eta_c + \gamma$ and the width of η_c .

At the end of the story there were two crucial contributions of Adone to the development of QCD:

- The measurement of R that was compatible with the colored quark model.
- The measurement of the decay widths of the ψ that were crucial in establishing directly the correctness of the colored gluon model.

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