Fifty years of research at CERN, from past to future: Experiment

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Abstract

An overview of fifty years of physics at CERN is given.

1 Introduction

I was asked to give a personal, selective, and informal review of half a century of physics at CERN. Actually I shall try to be as impersonal and objective as I can, and to cover as many of the important topics as possible. Nevertheless, there is no way to do justice to every actor and I apologize in advance for omissions and a minimal selectivity in my choices of topics. I shall be informal: by this I mean that I shall evoke the shadows as well as the lights.

In the preparation of this talk, I borrowed a lot from several colleagues, in particular the authors of the 25 and 50 years *Physics Reports* [1, 2], and from various historical accounts already published [3].

My own vision of CERN was that of an outsider before 1968, of an insider afterwards. I started my career in LAL Orsay, working at an electron linac on nucleon form factors which had been discovered in 1956 in Stanford (Nobel Prize awarded to R. Hofstadter in 1961) and on pion photoproduction, heavy lepton search, etc. Orsay exploited the first e^+e^- ring, AdA, coming from Frascati. Then the ACO e^+e^- ring allowed a detailed study of the vector bosons ρ, ω and ϕ. At the time ACO had to run flat out to reach the ϕ. A further ring of higher energy, COPPELIA, was considered, but the project did not go through, and the DCI ring was built instead. By that time, a group from LAL, led by P. Lehmann, decided to start an experimental programme at CERN and I joined it.

From these years of apprenticeship, I had learned that electron scattering and e^+e^- physics could be of high cleanliness and quality, that important discoveries may be made elsewhere than in your own laboratory, and that an e^+e^- ring has never enough centre-of-mass energy.

It was also clear that a cultural gap seemed to exist between electron and hadron communities. I am pleased to see that this seems to be over. The usual statement that a hadron collider is a discovery machine and an electron collider a measurement machine is a loose one, not supported by history. Electron-proton or e^+e^- collisions have revealed the structure of the proton, deep inelastic scattering (DIS), the J/Ψ, the τ, charm, jets, gluon. It has now been realized that an e^+e^- collider is a threshold machine. If the available energy $\sqrt{s}$ is below the interesting one you miss the possibility of a direct observation. The series of 'just missed' is long: ADONE trauma (J/Ψ, τ), DORIS (Υ), TRISTAN (Z^0), maybe LEP200 (h^0). Obtaining relevant indirect information is not guaranteed either. For instance, SUSY at LEP: in spite of all the accurate electroweak measurements performed, we still do not know whether SUSY, even light, is a reality or not. On the contrary, a hadron machine is not a threshold one but offers broadband beams of partons with tails at high energy, as Fig. 1 illustrates. One can, within some limits, trade energy against luminosity. A hadron collider offers a high potential for discovery, provided it is equipped with the right detectors. An e^+e^- machine is ideal for accurate measurements and detection of difficult final states, for example, invisible decays.

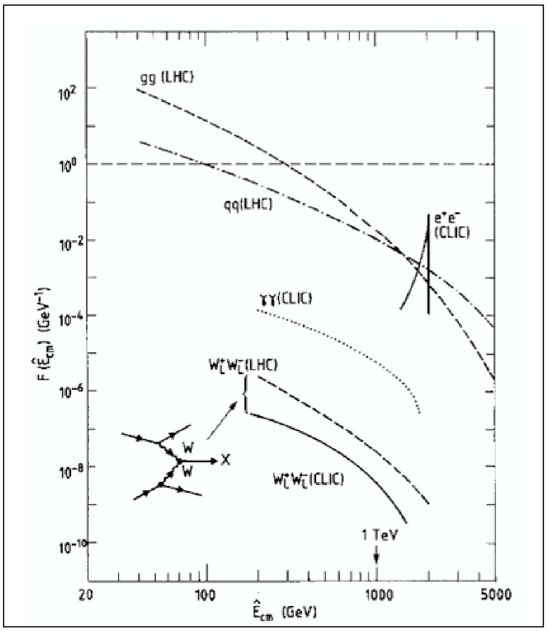


Fig 1: The scenery of hadronic and leptonic collisions (courtesy U. Amaldi)

2 Synoptic view of fifty years of particle physics

Table 1 below presents in chronological order some of the most important steps and innovations in four different sectors: theoretical physics, experimental physics, machines, and detectors. The ‘ideal’ physicist is the one who, at a given time, thinks in the proper terms, for instance after 1964 in terms of quarks and after 1973 in terms of the Standard Model (SM), goes to the most promising machine to perform experiments with the most efficient detectors.

A comment: it was always a great pleasure and help for me to be able to visualize the physical event: scanning of bubble chamber pictures, Ω optical, UA1 Megatek, DELPHI or ALEPH event display. Do the trends for the future keep that possibility?

Let me add some personal remarks:

In CERN scientific life, there were several very intense and euphoric periods: the era of bubble chamber physics, culminating with the discovery of Neutral Currents, the harvest of results from the SPS, the W and Z discovery, LEP1 and LEP200, etc. No doubt the LHC will be another one.

But we also went through some periods which, although they may have been intellectually stimulating, were quite depressing as seen from CERN: for instance, during the ‘1974 Revolution’ which followed the discovery of the J/Ψ in the United States, one had the feeling that ‘life was elsewhere’. Personally I also consider LEP200 as an unfinished symphony, as I shall illustrate later.

For long, CERN had a diversified physics programme. Most physicists had several ‘irons in the fire’, analysing an experiment, running another one, preparing a third. Currently, because of much longer time scales and in spite of the immensity of the task, there is a risk of monoculture and boredom. Could one conceive that young physicists share (unequally) their activity between the main line and a ‘small’ stimulating one?

Table 1: Some of the most important steps and innovations in fifty years of particle physics

	Theory	Physics	Machines	Detectors
1945	46 Gamow: Big Bang	47 π^- 47 Lamb	45 Synchr. McMillan	
	48–49 Feynman, Schwinger, etc., QED	47–53 Strange particles		47–50 Scint. count.
1950		51 Λ, K^0, Ξ^-		
	53 Gell-Mann (V particles)	53 ν_e Reines		53 BC (Glaser)
	54 CPT theorem			
1955		55 Antiproton	55 GeV e Stanford	
	58 Prentki–d'Espagnat	56 P violation	57 SC 58 first $g-2$	
	59 Regge		59 PS	59 30 cm BC
1960	61 Goldstone, Salam, Glashow Gell-Mann (8-fold way)		61 AGS	61 81 cm BC
	63 Cabibbo theory	63 Σ-Λ parity	63 First muon ring	
	64 Quarks: Gell-Mann, Zweig	64 Ω	64 ISOLDE	64 2 m BC
	64 Higgs mechanism	64 CP violation		
	64 Bell inequalities			
1965	66 Greenberg: colour			
	67 Sakharov conditions			
	67 Weinberg: ew Lagrangian		67 Budker e-cool.	
	68 Salam: ew Lagrangian			68 MWPC
	68 Veneziano's model			
	69 Bjorken scaling, partons	69 DIS	69 Second muon ring	
1970	70 GIM mechanism			70 Gargamelle
	71–72 't Hooft renorm.	72 ISR: hard coll.	71 ISR	72 OMEGA
	73 Asympt. freedom	73 Neutral Currents		
	Kobayashi–Maskawa	73 ISR: σ_{pp} increases		73 Split Field
	73 QCD+SM			73 BEBC
	73 Quark counting			
	73–74 Wess–Zumino	74 J/Ψ	74 Stoch. cool. proven in ISR	
1975		75–77 τ		
		75 jets in e^+e^-	76 Start of SPS	
		76 charm 77 Υ	76 $\bar{p}p$ idea	
	77 Altarelli–Parisi	78 PV at SLAC	77 ICE	78 † Gargamelle
	77 Peccei–Quinn	BEBC, .. :scal. viol.		78 ν beam-dump
	79 LEP Summer St.			
		79 Gluon at Petra		
1980	Phenomenology of SUSY	81 Beauty at CLEO	81 $\bar{p}p$ collider	81 Si microstrips RCBC
		82 Jets in hard. coll.	82 LHC feas. st.	
		83 W, Z discovery	83 LEAR	
	Supergravity	83 EMC effect		84 search for ν osc.
1985				85 End BC
	87 La Thuile workshop	86–87 B_s mixing, UA1, Argus	86 AC	
		88 Proton spin crisis		
		89 LEP: 3 ν	89 LEP	89 LEP detectors
1990	90 Large ED LHC Aachen Workshop		90 low-β UA2	

3 The mutations of the detector methods

One should remember that the ancestors of modern detectors are not so far away. While the Wilson chamber was born in 1911 and the Geiger–Muller counter in 1928, one had to wait until the years 1947–50 to see the first scintillators, the Bubble Chamber (BC) was invented in 1953, the MultiWire Proportional Chamber (MWPC) in 1968.

The first two decades of CERN life were the reign of bubble chambers. While the first was partly apprenticeship, the second decade saw the successes of the liquid hydrogen (LH) and heavy liquid (HL) large chambers. By the end of the life of this technique, rapid cycling BCs were successfully used for charm physics. The methods of analysis of their pictures were evolving in parallel and would deserve a paper by themselves [4].

Triggered detectors then entered the game. From 1949 to 1959 spark chambers (SC) were developed as tracking devices. The first massive use of SCs was at BNL in 1962, when evidence for the ν_μ was found. The various readout methods changed from film to filmless ones: acoustic, vidicon, wires. The OMEGA optical spectrometer was operated in 1972. In 1964 appeared the first online computers.

1968 saw the 'revolution' of G. Charpak, inventor of the MultiWire Proportional Chamber (MWPC), which then led to the drift chamber, the multistep chambers, a series culminating with the time projection chamber. The first large-scale use of MWPC occurred in 1971: the CERN–Heidelberg experiment, by J. Steinberger *et al.*, at the PS on CP violation and the Split Field Magnet, suggested by J. Steinberger and used by G. Charpak, A. Minten, P.G. Innocenti *et al.* (a cost of 23 MSF, unfortunately the detector was blind around 90º).

Cherenkov detectors, from threshold devices and focusing ones (DISC) to the Ring Imaging technique (RICH), have played a key role in particle identification. The RICH of T. Ypsilantis and J. Seguinot, after being used during the LEP era (DELPHI, SLD, heavy ions), seems to have a promising future ahead, an example being LHCb.

Concerning calorimetry, important breakthroughs were the understanding and exploitation of the compensation mechanism and the move towards pointing geometries, from the 'Spaghetti' to the ATLAS 'Accordeon'. Liquid argon and scintillating crystals are still quite fashionable.

Hybrid systems, from BEBC to the European Hybrid Spectrometer, have played an important role, in particular for charm physics.

Currently the ongoing revolution is the rise of silicon detectors. While the goal was flavour tag in the LEP era, one is now planning to use them as main tracker. This represents a big step, from the square metre typical of a LEP microvertex to hundreds of square metre, as for the CMS tracker at the LHC. Clearly this progress was made possible by various breakthroughs occurring in microelectronics, in particular the advent of submicron processes, intrinsically radiation hard, a very welcome feature for LHC experiments.

In all these mutations the crucial role of detector R&D (in particular the strong DRD programme undertaken to learn how to exploit the full luminosity of LHC) is obvious. It is clear as well that, if we want to progress further, some R&D has to continue. Whatever the physics goal may be (SuperLHC, ILC, CLIC, future fixed targets), some of the requirements are similar. For an optimal tracking one needs real 3D information obtained from pixels, micro or macro, rather than from stereo microstrips, maybe vectorial information (position and direction), thinner, faster, still harder and cheaper detectors. As for calorimetry, one is still far from a completely satisfactory design regarding its granularity and the integration of the electromagnetic and hadronic parts.

Figures 2 and 3 below give an idea of the evolution with time of the various classes of detectors. What is plotted is simply the number of entries in the search engine Spires whose title refers to a given technique. The fall of the curves does not imply that the technique is no longer used, but means that it no longer deserves a publication by itself.

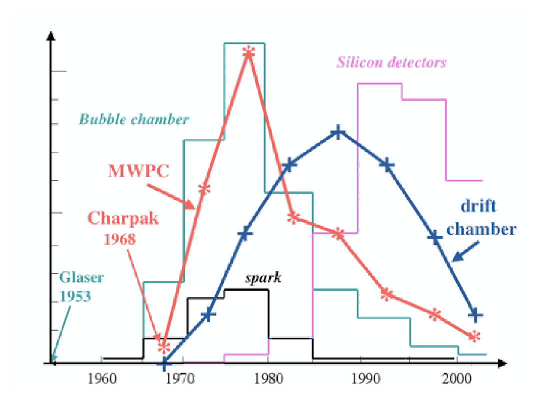


Fig. 2: Evolution with time of the various classes of detectors

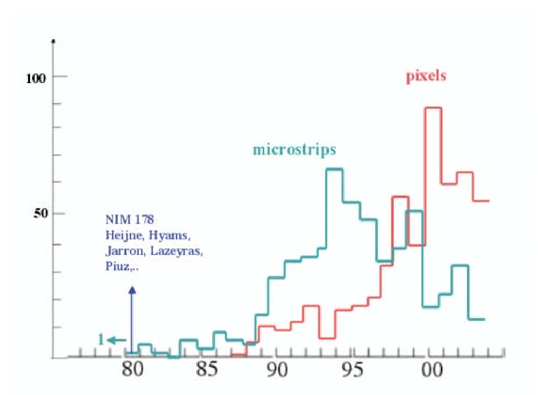


Fig. 3: More details on silicon detectors

4 The bubble chamber era

After the Second World War, the situation in the US and in Europe was quite different, politically and technically. Europe started with a period of 'every man for himself'. The various countries and CERN had to learn the techniques required and how to collaborate.

In 1953 the Bubble Chamber (BC) was invented by Glaser. L. Alvarez, in Berkeley, soon started to play a leading role in its development. CERN's interest in this technique started in 1955.

In 1956 many realizations and projects already existed around the world and the LHBC (liquid hydrogen) programme was adopted at CERN.

In 1955–56 J. Steinberger was developing propane chambers at Columbia University. In 1958 the HBC of 10 cm was in use at the synchrocyclotron, and lasted until 1960.

1959 saw the commissioning of the 72 inch chamber in Berkeley, recognized as the *"most courageous of scientific decisions"*.

From 1957 to 1960 CERN built the 30 cm LHBC, which was then in activity at the PS from 1960 to 1962. In 1960 the BP3 HLBC (heavy liquid) from Ecole Polytechnique in France was operated at CERN.

After 1960, having reached its maturity, the European bubble chamber community was able to react rapidly to new challenges and to take the right decisions which led to its notorious successes. In 1961 the Track Chamber Division was created under C. Peyrou, its mission being to run the 30 cm BC, to build the 2 m one and to get hydrogen liquefiers.

In 1961, the 81 cm LHBC from CEA started operating at CERN. In 1961 the 1 m HLBC from Ecole Polytechnique in Paris came to CERN. The magnetic horn, invented by S. van der Meer and completed in 1962, led to a very welcome increase in neutrino fluxes.

By the end of 1963, a 2 m BC was being operated in Berkeley and Brookhaven. In January 1964 appeared R.P. Shutt's proposal, telling that times were ripe to build very large chambers. The reaction in Europe was fast. In February–April 1964 Gargamelle was defined (A. Lagarrigue). By mid-1964 the 152 cm British National HBC was put in service at CERN. In December 1964 the realization of a large LHBC was recommended, the Tripartite Technical Group was created. 1965 saw the start of operation of HBC 2 m (cost: 3 MSF, operated until 1977, 40 million pictures taken). At the end of 1965 came the decision to build Gargamelle, commissioned in December 1970. The construction of BEBC lasted from 1967 to 1972; in 1975 it was fully operational.

Given the initial situation described above, it is not surprising that the first important discoveries of the BC era were made elsewhere than at CERN.

Let us quote:

- At the LBL cyclotron in 1950: $\pi^0 \to 2\gamma$ (Panofsky, Steinberger)
- At other machines:

1953: BNL Cosmotron, 3.3 GeV proton synchrotron, exploited until 1966
    1953: V^0 events **1956:** K_L **1957:** Σ^0 **1961:** ρ
1955: LBL Bevatron, 6 GeV protons
    1955: discovery of antiproton
    1958: anti-Λ **1959** Ξ^0 **1960** anti-Σ^0
    1961: $K^*(892)$, $\Lambda(1400)$, ω, η **1964:** η'
    1968: Nobel prize awarded to L. Alvarez
July 1960: AGS, 33 GeV
    1964: discovery of Ω^-, discovery of CP violation

Nevertheless one must recognize many important contributions to hadron spectroscopy from CERN in the first years. For instance in 1962, using K^- at rest, the 81cm HBC allowed one to measure the relative $\Sigma - \Lambda$ parity, found to be > 0, or the observation of the anti-Ξ (Fig. 4).

Later came the great successes of the big chambers, crowned by the discovery of Neutral Currents. Finally, an important role in charm physics was played by the last generation of small rapid-cycling chambers. Moreover, bubble chamber activities have gradually built the strong and diverse CERN technical expertise. It is from them that Europe and CERN found the way to collaborate.

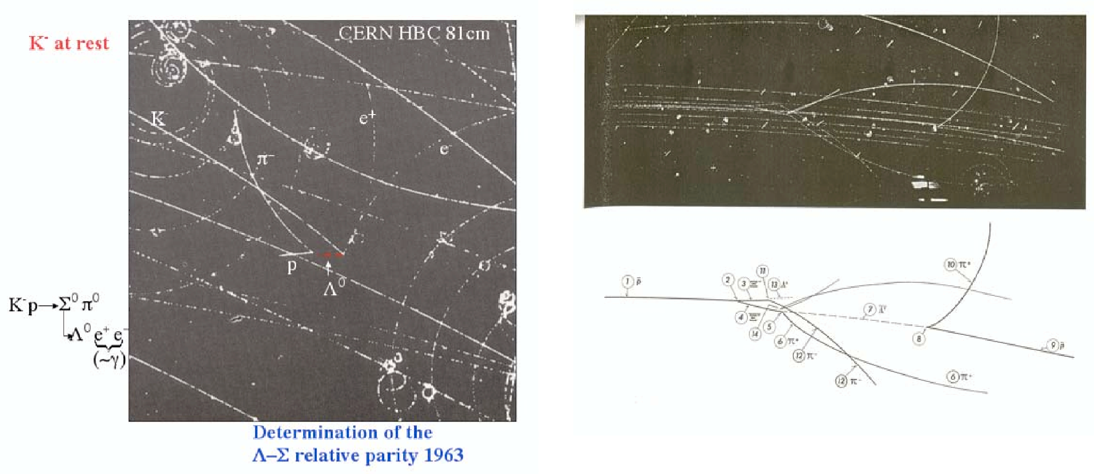


Fig 4: A Σ–Λ event (left); the first Ξ–anti Ξ event (right)

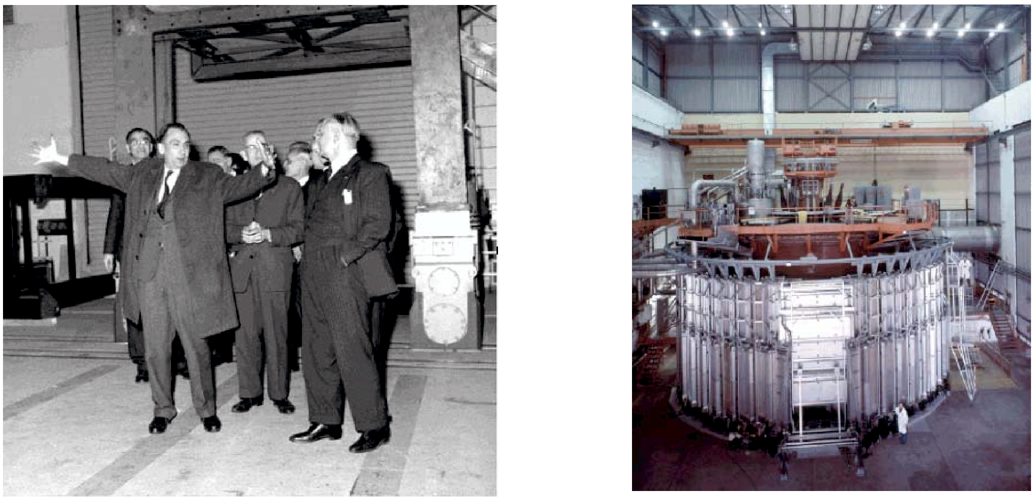


Fig 5: C. Peyrou and BEBC

4.1 Early non-BC physics at the Synchrocyclotron [5]

Considering the $\pi \to e\nu$ channel, in 1955 J. Steinberger at Nevis Lab had set an upper limit on its branching ratio R_e ($< 0.6\ 10^{-4}$) and this started to be puzzling. However, in 1958, G. Fidecaro *et al.* got evidence for its existence and found $R_e = (1.22 \pm 0.30) \cdot 10^{-4}$. This was in agreement with the expected e–μ universality of the axial coupling and a cornerstone of our understanding of V–A interactions.

For the process $\mu \to e\ \gamma$, it was the reverse. Some evidence of its existence had been reported. However, in 1962, Conversi, di Lella, Rubbia *et al.* showed that the process was forbidden, both for real and virtual γ. The idea of lepton-flavour conservation was introduced.

Let us quote also the first observation of the pion β-decay $\pi^+ \to \pi^0 e^+ \nu$.

Experiments on the $g-2$ of the muon started at the SC in 1958. One should also mention the determination of the helicity of the muon from $\pi \to \mu\ \nu$ at the PS.

4.2 Neutral Currents (NC)

I borrowed much from several excellent chronicles about Neutral Currents [6–8].

From the 1.2 m HL chamber, there was an upper limit on the ratio of elastic NC to Charged Current (CC) events (< 0.03), published in 1964. This was simply a mistake uncovered by M. Paty in 1965.

After the Siena 1963 conference, A. Lagarrigue, A. Rousset, P. Musset worked out a proposal of a neutrino detector aiming at increasing the event rate by an order of magnitude. L. Leprince Ringuet called it Gargamelle. The team was composed of physicists from X-Orsay and of former members of the NPA 1 m BC. It included seven European laboratories and one guest laboratory.

In 1971–72 a viable theory of weak interactions existed and the question was clearly posed: are there NCs, yes or no? The competitors in the field were Gargamelle and the HPWF counter experiment at NAL.

Even in November 1968, at a Gargamelle meeting in Milan, the word NC was not pronounced. This problem had low priority and Deep Inelastic Scattering (DIS) was more exciting then.

But in 1971 everything was ready. A careful classification of event types was devised. NC events looked like neutron star events without a muon. The goal was to separate neutrino-induced from neutron-induced stars.

In December 1972 one electron event was found at Aachen. The search for hadronic NC candidates went on. Candidates were observed, with a flat spatial distribution, and caused much excitement. However, counter arguments were put forward and one realized that the only way to conclude was to prove that the number of neutron-induced events was small. Monte Carlo simulation then showed its strength: a neutron background program with no free parameter was used, complemented by other approaches. It allowed the conclusion that the NC sample was not dominated by neutron stars (J. Fry and D. Haidt, CERN Report 75-01). At the Bonn 1973 conference, C.N. Yang announced the discovery of Neutral Currents.

However, by that time the HPWF signal had disappeared. This threw dismay and distrust on the whole matter, and one more year of work was needed to conclude. Finally, at the London 1974 conference, evidence for NC was confirmed by Gargamelle and HPWF.

This major discovery established the similarity in structure of the weak and electromagnetic interactions. The term 'electroweak' came into being. This was the experimental beginning of the SM. The M_W was then predicted to be around 70 GeV.

Fig. 6: André Lagarrigue and visitors

Fig. 7: André Lagarrigue

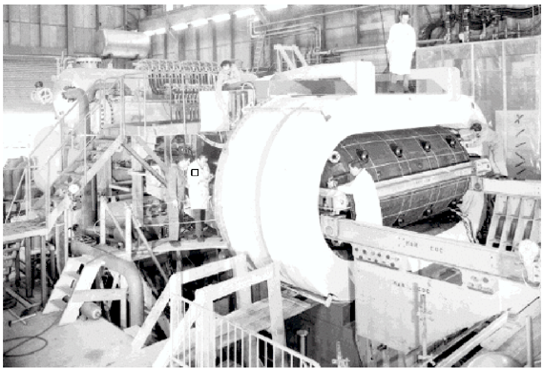


Fig. 8: Gargamelle

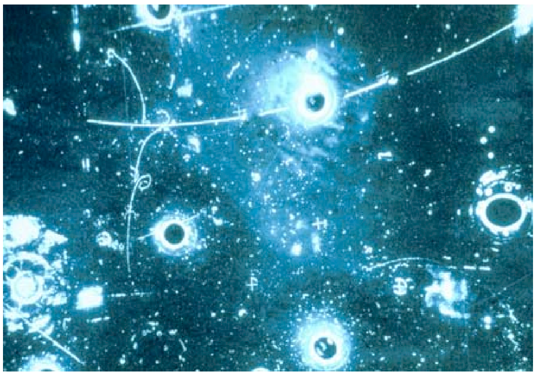


Fig. 9: A neutral current event on electron

Fig. 10: S. van der Meer

Fig.11: A. Salam with P. Musset (right)

Fig. 12: A. Salam receiving the Nobel Prize

4.3 Other important results from the bubble chambers

Besides Neutral Currents the large bubble chamber brought other most interesting results.

By comparing the structure functions of the nucleon derived from neutrino and muon scattering, Gargamelle proved that quarks have indeed a fractional electric charge (Fig. 13).

Gargamelle demonstrated that the neutrino–nucleon cross-section rises linearly with energy (Fig. 14).

Finally, by combining their results, BEBC and Gargamelle got the first evidence for scaling violation (Fig. 15), namely the proof that the nucleon structure functions actually evolve with the resolution power of the observation.

An amusing fact is illustrated by Fig. 16. At that time, the value found for the Weinberg angle was in agreement with non-supersymmetric Grand Unification. This predicted a rather low GU scale and a proton lifetime of 10^{30} years or so. This prompted programmes aimed at detecting proton decay, like Kamiokande. They did not find proton decay because the value of the Weinberg angle was actually incorrect. But they later discovered the non-zero neutrino mass via ν oscillations!

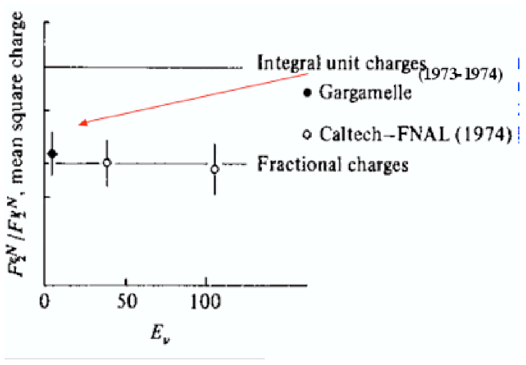


Fig. 13: The charges of quarks are fractional

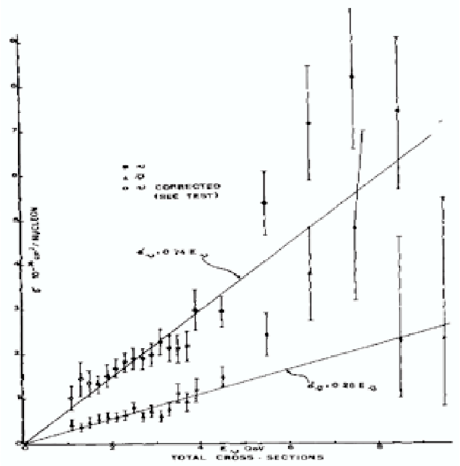


Fig. 14: The rise of the neutrino cross-section

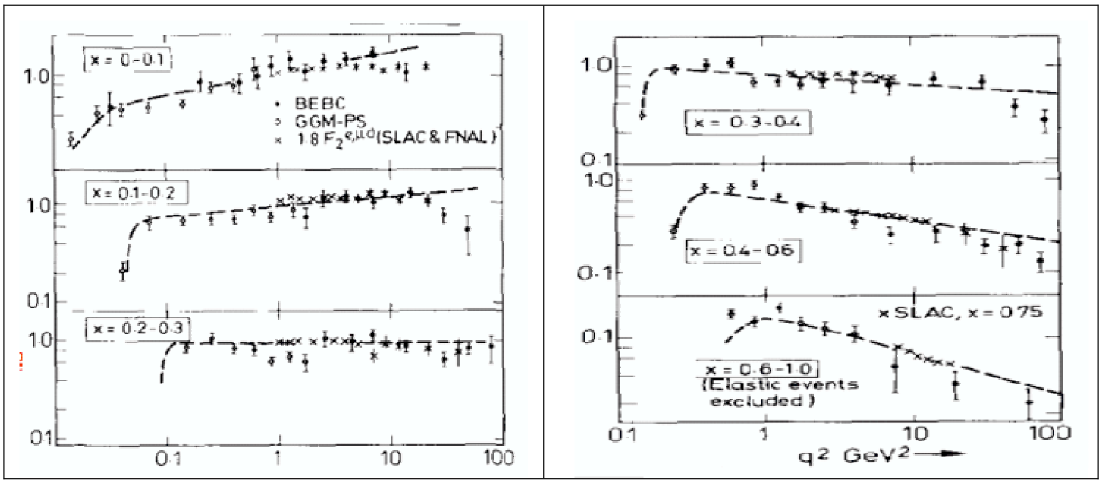


Fig. 15: First evidence for scaling violation

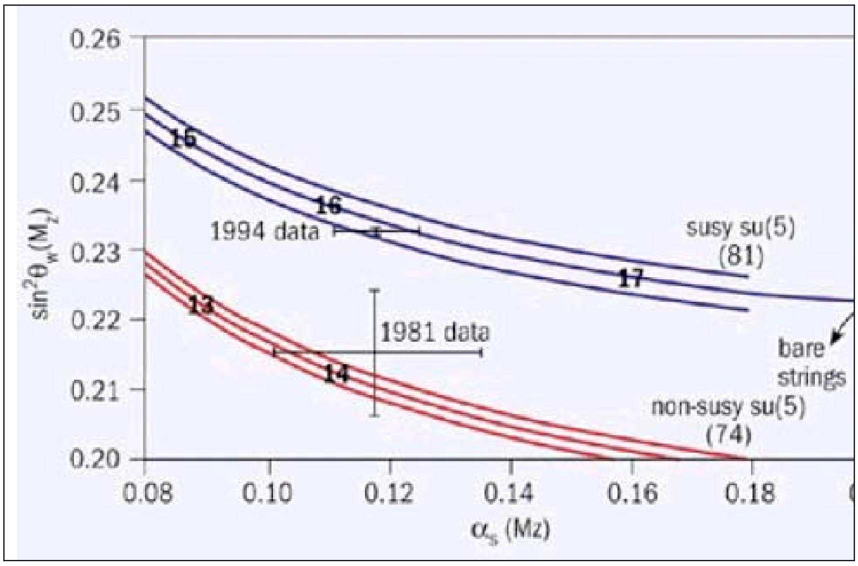


Fig. 16: *Ad augusta per angusta:* the status of the mixing angle in 1981

5 The ISR

The Intersecting Storage Rings (ISR) was the first hadron collider ever built. Following M. Jacob we distinguish:

- “A brilliant start”: 1971–74

An important early discovery at the ISR was the rising total proton–proton cross-section in 1971. The measurements led us to conclude that, while the proton size increases with energy, its profile stays the same.

Another major finding was the discovery of the large p_T phenomena at the ISR in 1973 (Fig. 17): it demonstrated that partons were behaving as pointlike objects for the strong interaction as well as for the electromagnetic one.

The study of Diffractive Dissociation told how energy hadronizes, independently of the nature and energy of the colliding particles.

- “A somewhat difficult period”: 1975–77

The reason, obviously, is that several important discoveries (J/ψ, charm, beauty) within reach of the ISR were actually made in the US (see the synoptic table), in part because the ISR detectors were not adequate.

- “A very active and interesting programme”: 1978–83

Among other topics one can mention the studies of lepton pair production: J/ψ, Y, dilepton masses up to 20 GeV, properties of the Drell–Yan process. However, charm and beauty semileptonic decays were ignored in these data analyses. Concerning the production of heavy quark bound states, like $pp \rightarrow \chi_C$, the results obtained at that time are still competitive.

The first clear mass peaks of charmed hadron production in hadronic interactions were observed in 1979, following several earlier indications from the measurements of single electron and lepton pairs. However, the charm cross-section determination turned out to be troublesome. The production of a beauty baryon at the ISR was announced but was for a long time a controversial matter.

The production of direct photons was studied, from their discovery in 1979 to the end of the ISR (Fig. 18). These measurements played an important role in testing QCD. Gluon Compton scattering was found to be dominant, the sub-leading process being quark–antiquark annihilation. This fact allowed the determination of the gluon distribution inside the proton. The study of the two-photon final states was also performed. A comparison of the yields with antiproton–proton collisions would have been interesting, but unfortunately the luminosity was insufficient.

Concerning the evidence for jets in hadronic collisions, it started with a rather confusing period, both in fixed-target experiments and at the ISR. By 1982 the AFS and R110 experiments at the ISR had an appropriate acceptance to see jets. But the results of the proton–antiproton collider came at about the same time, and these ‘stole the limelight’, although different *x*-regions were probed in the two sets of measurements.

Whatever be the area of the physics programme, the machine worked magnificently: the ISR were a most efficient R&D laboratory for accelerator physics. In particular, it allowed the testing of the idea of stochastic cooling, key of later successes.

By the end of the ISR in 1983, M. Jacob, quoting Mark Antony, in Shakespeare’s Julius Caesar, said: “I come to bury Caesar not to praise him”, while V. Weisskopf argued that it does not matter where discoveries are made.

Nevertheless, the morale at CERN was low. In one of the pictures, V.Weisskopf seems to exhort us to turn to superior instances. That is what we did in a quite oecumenical way.

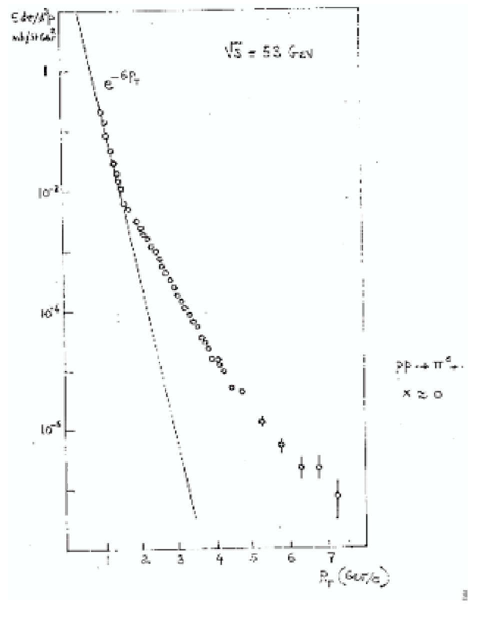


Fig. 17: The high p_t signal at the ISR

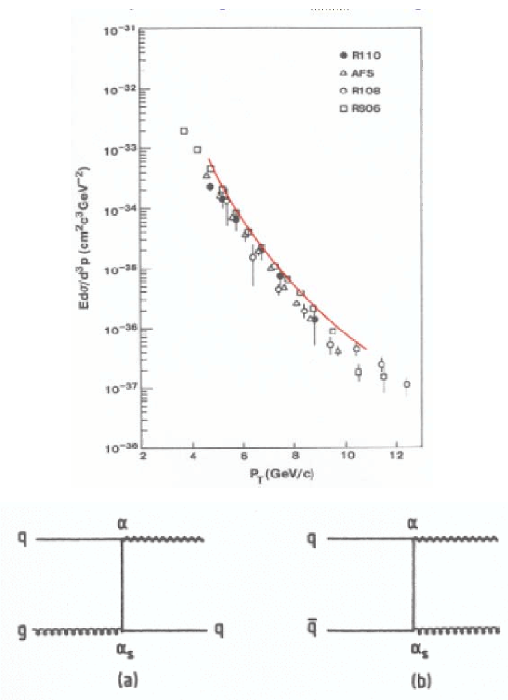


Fig. 18: Direct photons and dominant diagram

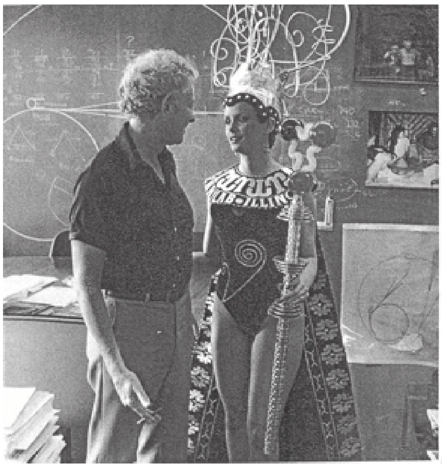


Fig. 19: L. Lederman discovering beauty

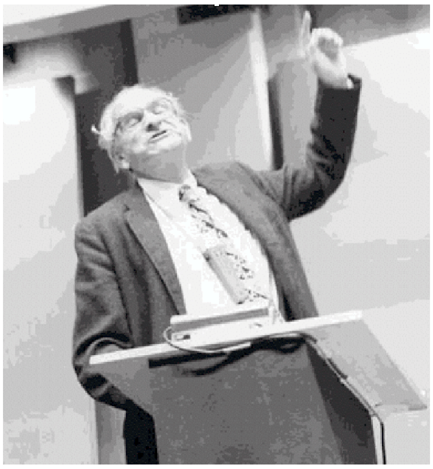


Fig. 20: An exhortation of V. Weisskopf

Fig. 21: Visit of the Pope

Fig. 22: Visit of the Dalai Lama

6 The proton–antiproton collider

Actually the real cure came from the success of the proton–antiproton collider.

A look at the synoptic tables shows how fast were the decision-making and the realization of this programme. The collider was a great machine, largely due to the use of stochastic cooling. It fed two outstanding and quite innovative detectors. For the first time, concepts like hermeticity of a detector, redundancy of the procedures, etc., were fully taken into account. The figures below show the UA1 detector and a sketch of its powerful tracker.

As we all know, “la physique était au rendez-vous”. Besides the most celebrated discovery of the W and Z bosons, close to the predicted masses, the collider brought a clear picture of hard hadronic scattering [9].

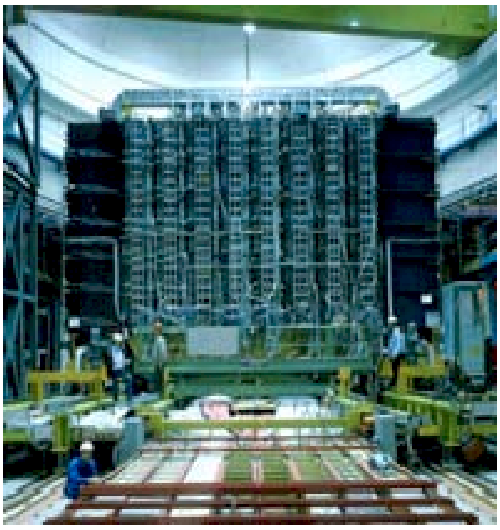


Fig. 23: The UA1 detector

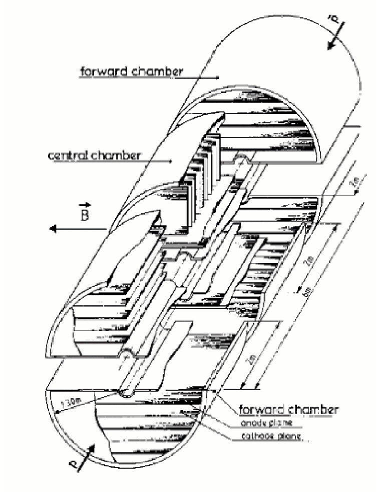


Fig. 24: A sketch of the UA1 tracker

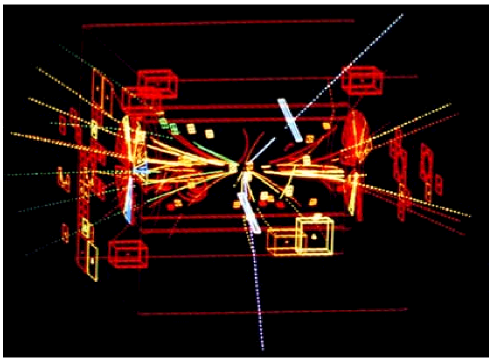


Fig. 25: First Z event in UA1

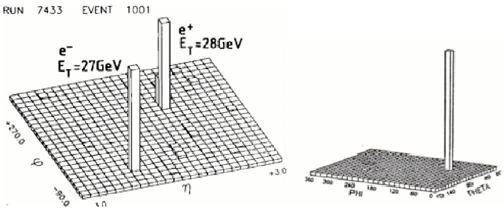


Fig. 26: Lego plots of a W and Z event

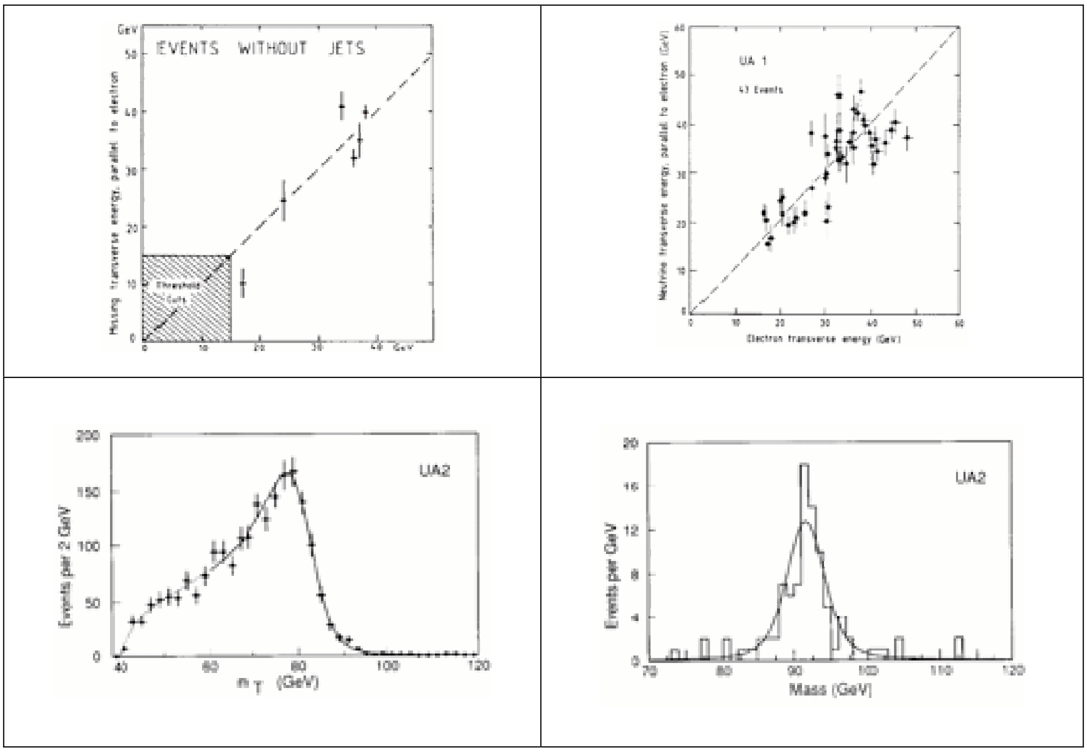


Fig. 27: From the discovery to the final UA2 results

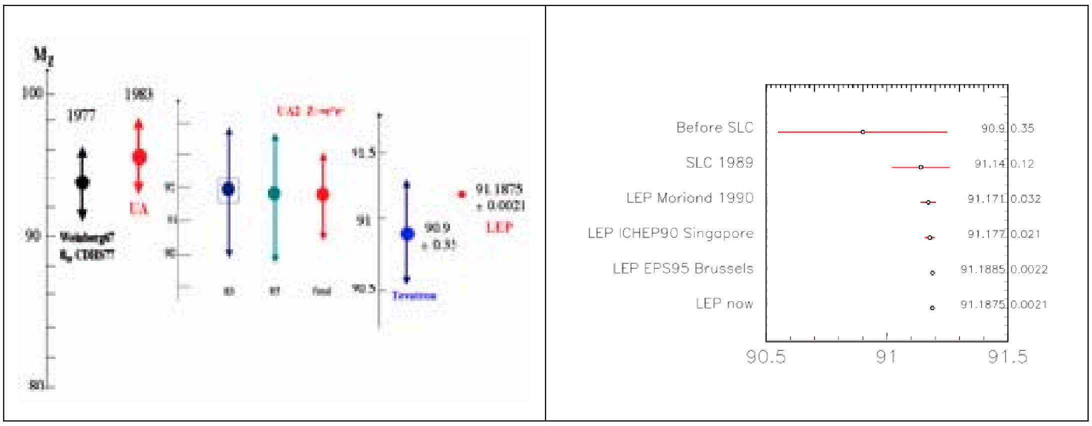


Fig. 28: Evolution of the Z mass, from its prediction to LEP final results

Let me tell you more about hard hadronic scattering.

In 1981 the fixed-target NA5 experiment, with full azimuthal calorimetric coverage, did not see any jet structure. The situation in hadronic scattering was thus very different from the one of e^+e^- scattering in which a clear two-jet structure had been observed since 1975. Even after the first run of the collider the results were not decisive. However, in 1982, first UA2, then UA1 obtained clear, uncontroversial evidence for jets. UA2, for instance, had a full azimuthal and a 40° to 140° polar angle coverage.

Many results then followed, among them:

- the determination of the angular distribution of parton–parton scattering,
- the determination of the proton structure functions, showing the role of gluons at small x,
- the production of direct photons, found to agree with NLO QCD,
- the measurement of the total p_t of two-jet systems, agreeing also with QCD,
- the studies of multijet final states, of the W transverse momentum, of heavy flavour production (beauty), all behaving as expected.

The collider thus proved the physical reality of partons inside the proton and opened the door to quantitative tests of QCD.

Much progress has been obtained since then, in particular by the Tevatron proton–antiproton and HERA electron–proton colliders. What remains to be done, concerning QCD, in order to guarantee a proper search programme at the LHC, is impressive as well.

7 The SPS Programme

The programme was carefully prepared in 1970–74 by a prospective activity on the SPS beam lines and on its physics programme, in particular at the ECFA Tirrenia Meetings.

7.1 Neutrinos

This programme has been one of the flagships of CERN activities. From its start in 1976 the SPS narrowband beam, up to 200 GeV, and wideband beam, 10^2 times more intense but peaked at low energy, fed, in addition to the Bubble Chambers BEBC and Gargamelle (ending in 1978), the giant spectrometers, CDHS and CHARM, and later CHORUS and NOMAD.

These experiments performed more and more refined measurements of scaling violation, of α_S and of the nucleon's gluon content. In conjunction with electron and muon DIS, they confirmed, as we saw, the fractional electric charge of u and d quarks ($F_2^{eN} = 5/18\ F_2^{\nu N}$). Since parity violation allows neutrinos to distinguish quarks from antiquarks, their scattering provided the structure functions of the 'sea' quarks. Opposite-sign dimuons were exploited to get the structure function of the sea of strange quarks in the nucleon.

Later the neutrino programme included a beam-dump experiment, and finally moved to the search for oscillations, unfortunately in a domain of parameters in which, as we know now, they could not manifest themselves.

7.2 Muons

This programme has been active from 1978 to now. The most efficient and clean SPS muon beam (R. Clifft, N. Doble) first fed the NA2 (EMC) and NA4 (BCDMS) experiments, which took data until 1985. Afterwards, EMC became New (or Nuclear) MC then SpinMC. The programme is currently continuing with COMPASS.

Scaling violations, first seen in BC neutrino data, were studied in great detail using the Altarelli–Parisi formalism (1977). Various tests of perturbative QCD and a precise measurement of the strong coupling constant were performed.

In 1983 the EMC effect (Fig. 29) came as a surprise: the structure functions of the nucleon depend on the nucleus in which it is immersed. In 1988 another surprise was the proton spin crisis (Fig. 30), deduced from the study of spin-dependent structure functions. The total quark spin, contrary to expectations, is only a small fraction of the proton spin. These two effects are far from being explained and other programmes, COMPASS, HERA polarized, HERMES, RHIC p–p polarized, will continue to shed light.

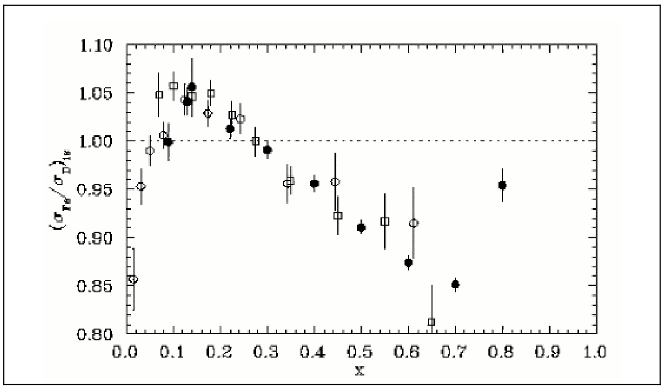


Fig. 29: The EMC effect

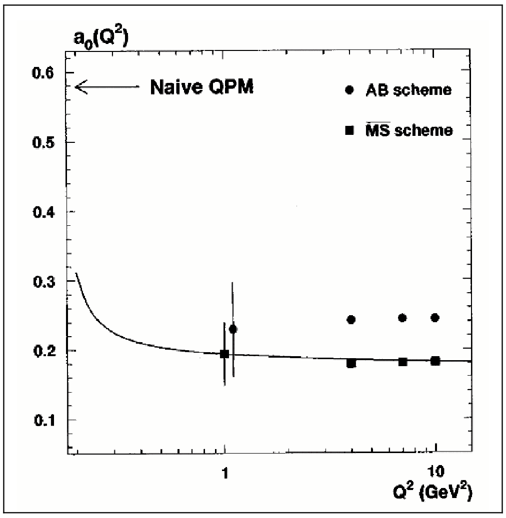


Fig. 30: The spin crisis

7.3 Hadron and photon beams

This very rich programme includes about 70 experiments extending over 25 years. The main themes of physics can be classified as follows:

- Hard scattering
- Heavy flavours
- Hadron spectroscopy
- Soft processes.

Hadron spectroscopy covers in particular the spectroscopy of light quarks, glueball searches, baryonium searches. Soft processes include studies of particle production, elastic scattering, low-mass $\mu^+\mu^-$ pairs, soft photons, etc.

Forced to be selective, I have chosen to illustrate the first two items.

7.4 Hard scattering

The main activities were the study of high-mass lepton pairs or the Drell–Yan mechanism. A highlight was the discovery of the K factor in NA3 (Fig. 31) and WA11 in 1982, namely direct evidence for higher-order QCD corrections. Being essentially a multiplicative factor of the cross-section, constant with Bjorken-*x*, this K factor did not preclude the study of structure functions, in particular those of unstable hadrons like pions and kaons.

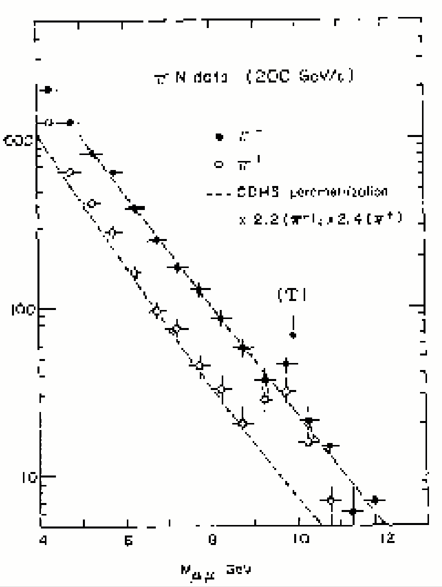
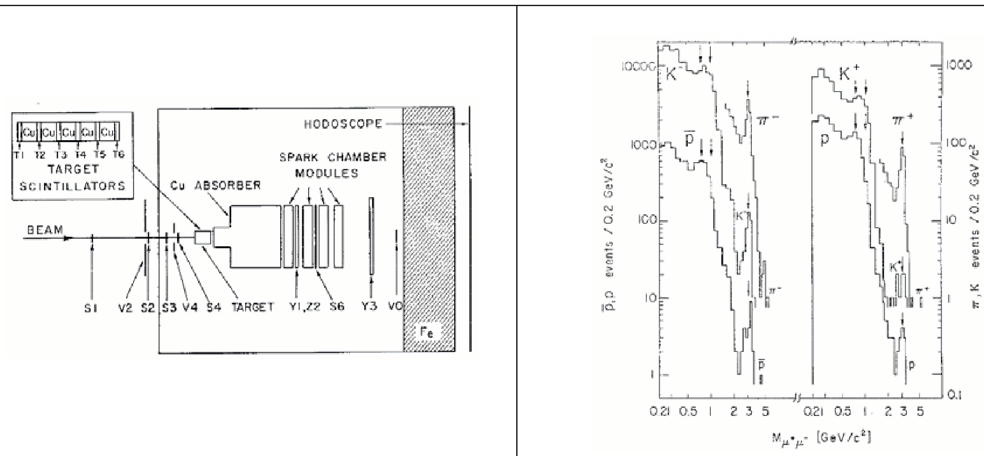


Fig. 31: Evidence for the K factor from NA3

Among other experiments, one can quote the Omega Beam Dump in 1978, measuring J/ψ and Drell–Yan dimuon production by a variety of projectiles, and which provided the very first results obtained from the SPS (Fig. 32).



(a) (b)

Fig: 32: The Omega beam dump, set-up (a) and results (b)

Another active area was the study of prompt single photons and di-photons produced in hadronic reactions, bringing some first-hand information on the hard processes.

Photoproduction, besides charm studies (see later), provided the first high-energy measurement of the Compton effects on quarks in 1985–86: QED Compton effect, i.e., elastic scattering of the gamma on a quark (Fig. 33), and QCD Compton effect, a process in which the incident photon is changed into a gluon.

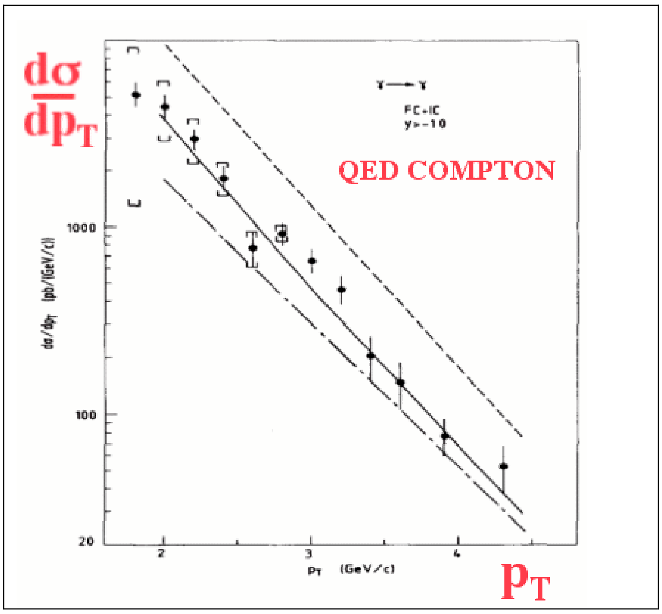


Fig. 33: Evidence for QED Compton from NA14

The comparison of experimental data with the existing theoretical QCD estimates, computed at the relevant order of perturbation, contributed strongly to validating the theory.

7.5 Heavy flavours

I shall insist a bit more on heavy flavour physics, a very active sector as well (about 20 CERN experiments), not only because of its impact on QCD testing, but also because it was a most innovative sector in terms of high-spatial-resolution silicon detectors, like microstrips, CCDs and active targets. It used also ‘old’ techniques, like emulsions coupled with large spectrometers, and rapid cycling bubble chambers. All types of beams were exploited: hadrons, photons (which offer a fraction of charm ten times higher than hadrons), and hyperons. It contributed mostly to charm physics, but provided also some results on beauty, obviously a more difficult physics topic requiring higher energies.

Figure 34 illustrates a few remarkable results: the associated production of charm in emulsions (WA58), of beauty in the microstrips of WA92, the very pure signal of $\Lambda_C \rightarrow pK\pi$ from NA32, thanks to its CCD detectors, and the signal of Ω^0_A of WA89, the shortest lifetime ever measured that way (5×10^{-14} s).

Figure 35 recalls two beautiful experiments performed at CERN.

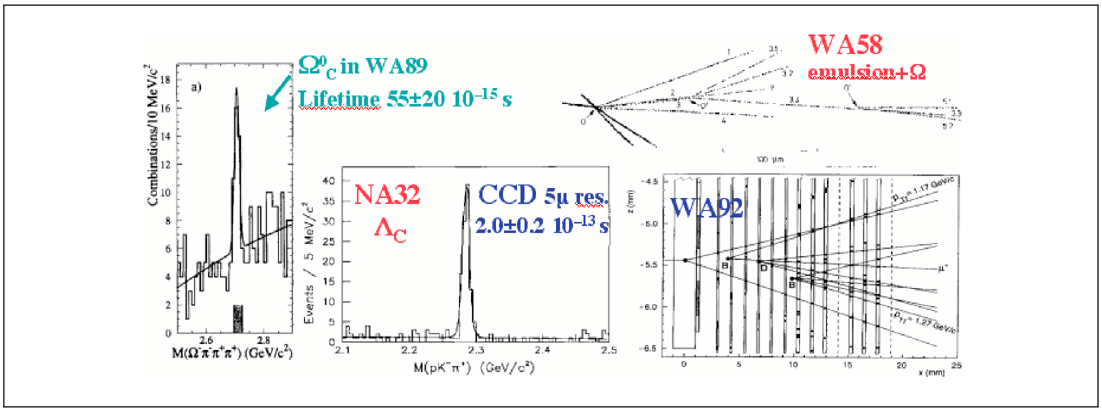


Fig. 34: A few results from heavy-flavour physics (see text)

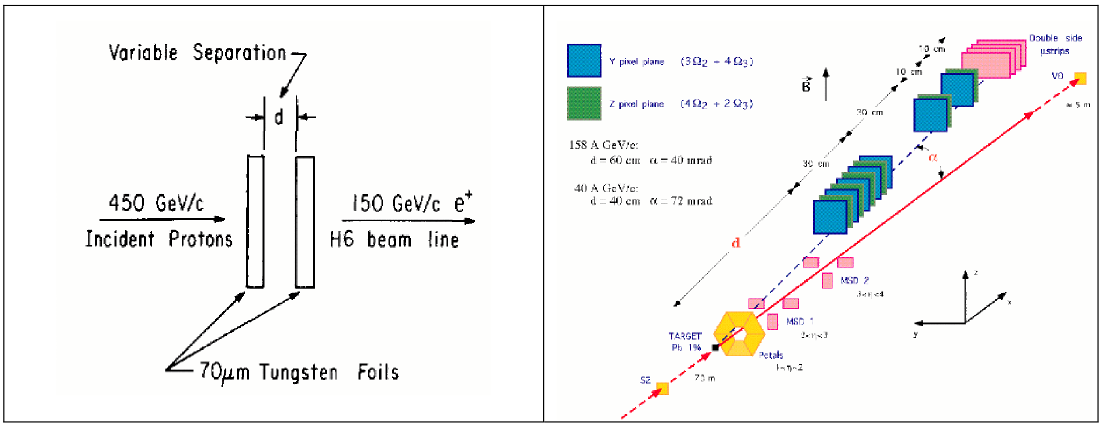


Fig. 35: Two remarkable experiments: the π^0 lifetime (CERN SPS, 1985) and the pixel set-up of NA57

8 Accurate tests of gauge theories

8.1 *g*-ology

The $g-2$ programmes have extended over 40 years. As John Adams once said: *"$g-2$ is not an experiment: it is a way of life"*. Indeed some of the initiators are still currently involved. From my point of view it represents one of the most beautiful achievements in particle physics, experimentally and theoretically.

The g factor is the constant that determines how much magnetic moment μ results from a given amount of charge, mass and spin s, $\mu = g$ e/2m s. For the electron or muon the Dirac equation gives $g = 2$. Actually a slight difference arises because of radiative phenomena (Fig. 36) and the $g-2$ quantity turns out to be an amazing testing ground of theory, QED and EW, since all interactions contribute to it. The present measurements of g are

- electron: 2.0023193043718 ± 0.0000000000075, i.e., a few parts per trillion.
- muon: 2.0023318416 ± 0.0000000012, 'only' a few parts per billion, but with the potentially interesting effects boosted by the mass squared factor (40 000).

The confrontation between experiment and theory has been a “tennis game with well-matched players on either side of the net ”, actually a 40-year long experimental programme matching a 40-year long programme of more and more refined calculations. At first order: $\alpha/2\pi \sim 0.00116$, giving $g = 2.00232$. There are 7 two-loop diagrams, 72 three-loop diagrams computed in 1995 by T. Kinoshita at Cornell (at better than one part per million), 891 four-loop diagrams, for which numerical computations have bean under way since early 1980, and 12672 five-loop ones. The role of hadronic light-by-light scattering is important and actually leads to the present residual ambiguity in the interpretation.

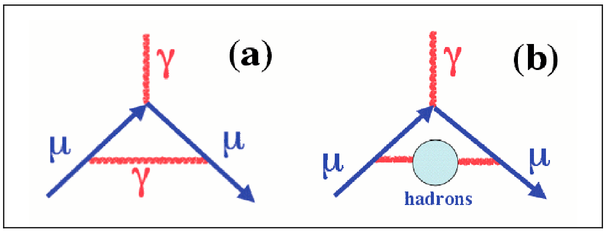


Fig. 36: (a) The one-loop contribution to $g-2$; (b) a key higher-order contribution

The value of $g-2$ is obtained by measuring the beat between the rotation of muons around a ring and the rotation of their spin. The movement of the spin is described by the Bargmann–Michel–Telegdi equation.

In 1958 a first experiment was done at the SC. The actors are shown below.

In 1963 came the idea of a new experiment at the PS with 1.2 GeV muons involving E. Picasso, S. van der Meer, F. Farley, F. Krienen *et al.* The signal was observed for ~130 microseconds. A disagreement of 1.7 σ between experiment and theory led to a correction of the latter.

A better experiment started in 1969, using the so-called magic γ-factor at 3.1 GeV, the energy at which the electric field does not affect the g–2 precession, so that one can use electric quadrupoles with a uniform magnetic field. The signal was observed for 534 microsecond, the agreement with theory was excellent.

In his tribute to E. Picasso, F. Farley [10] underlined the excellent atmosphere in the group: “no wars, no clashes”.

Figures 37 to 43 illustrate various aspects of the $g-2$ programme.

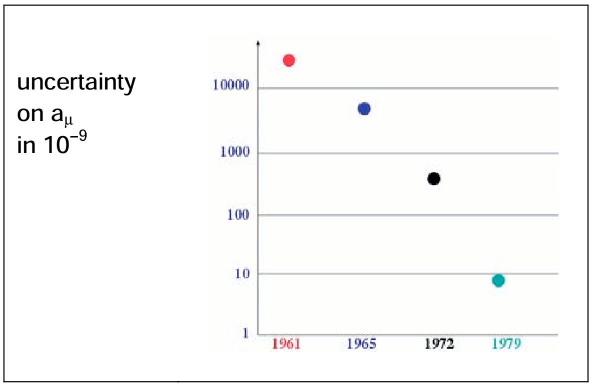


Fig. 37: The evolution of the uncertainty in the CERN experiments

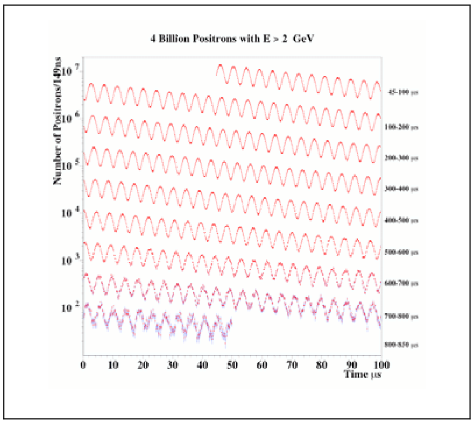
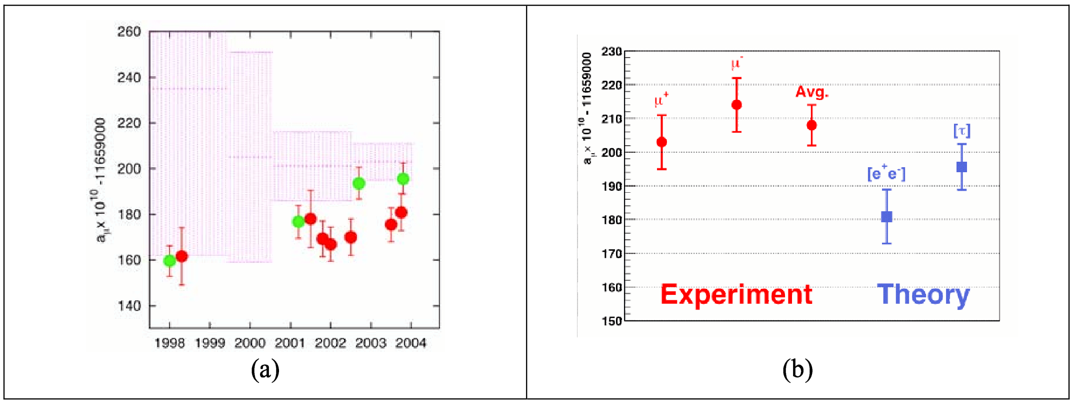


Fig. 38: The signal in the Brookhaven experiment



(a)

(b)

Fig. 39: The present status of the confrontation between experiment and theory

Fig: 40: The team of the first $g-2$ experiment

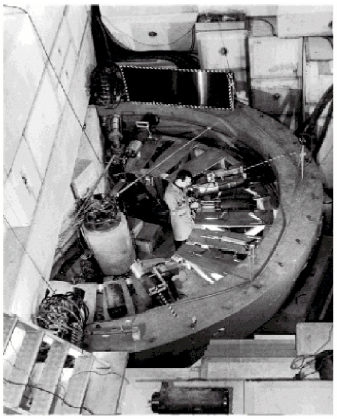


Fig. 41: The first ring

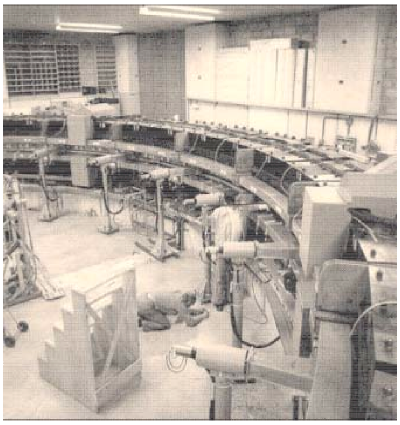


Fig. 42: The second ring

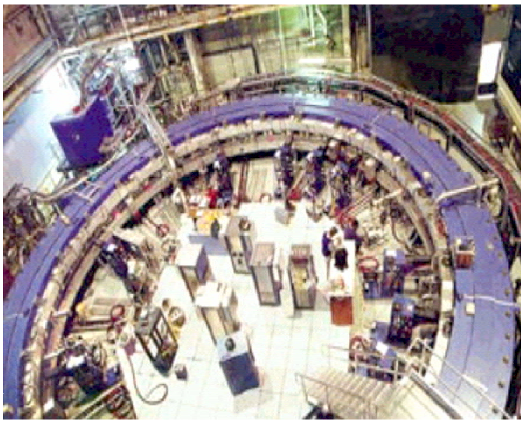


Fig. 43: The Brookhaven ring

9 LEP and ADLO

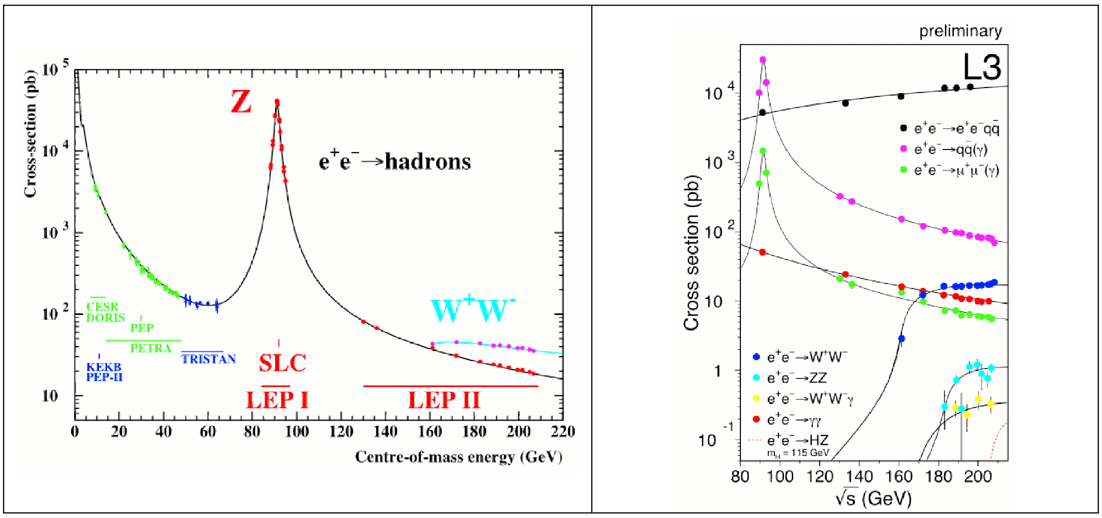


Fig. 44: The LEP scenery

ADLO is the name of the four experiments, ALEPH, DELPHI, L3 and OPAL, which combined their results.

LEP is a well celebrated success story. The machine, planned very accurately 15 years in advance, worked magnificently, surpassing all expectations (see Table 2). The superconducting radiofrequency cavities, on account of a careful work of conditioning and balancing, reached an accelerating field substantially higher than expected. The vacuum, thanks to the large-scale use of getter pumping, was outstanding, and this contributed to very favourable experimental conditions.

LEP was exploited by four high-quality multipurpose detectors. The programme led to clean and subtle physics results: in particular it demonstrated the validity of the SM at the loop level. Through their effect as virtual objects, it gave results on particles too heavy to be ‘really’ produced, the top quark and the Higgs boson. It showed that the coupling ‘constants’ of the three forces, electromagnetic, weak and strong, are actually running and converge exactly at a very high scale (~10^{16} GeV) in the supersymmetric version of the SM. We briefly quote below the main LEP messages.

We recall that, besides the main programme, two additional variants of LEP were studied. Even if they were not realized, these studies had interesting consequences. The first was an attempt to exploit the longitudinal polarization of $e^\pm$ at LEP. It turned out to be complicated and, since it would have delayed the LEP energy upgrade, it was not implemented. It led to the invention of a clever scheme, called the Blondel scheme, which may play an important role in the future at a Z factory, and to exploit transverse polarization, key to the precise measurement of the Z mass. The second variant aimed at a much increased luminosity by devising multibunch schemes (Pretzel trains later replacing equidistant bunches in the Pretzel scheme). Actually up to 16 bunches were used, and LEP can be considered as a first approximation of a Z and therefore of a heavy-flavour factory.

Table 2: LEP performance: foreseen and achieved

	Foreseen (55/95 GeV)	**Achieved (46/98 GeV)**
Current per bunch	0.75 mA	1.00 mA
Total current	6 mA	8.4 mA/6.2 mA
Beam–beam vertical parameter	0.03	0.045/0.083
Ratio of emittances	4.0	0.4%
Maximal luminosity (10^{+30})	16/27	34/100
β_x^*	1.75 m	1.25 m
β_y^*	7 cm	4 cm

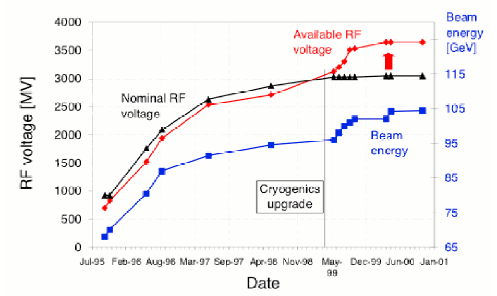


Fig. 45: The RF voltage around LEP

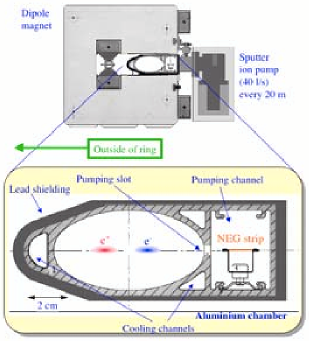


Fig. 46: The vacuum chamber and its getter pumping

In all respects LEP experiments did better, sometimes much better, than expected as shown by Table 3 below.

Among the instrumental breakthroughs which contributed to these successes, let us quote:

- the use of high-performance luminometers and the most accurate theoretical knowledge of the relevant Bhabha cross-section (Figs. 50, 51), a key indredient of neutrino counting (Fig. 52);
- the exploitation for beauty tagging of high-quality silicon microvertex detectors, allowing excellent purity for a still reasonable efficiency (Fig. 53).

Fig. 47: The LEP inauguration

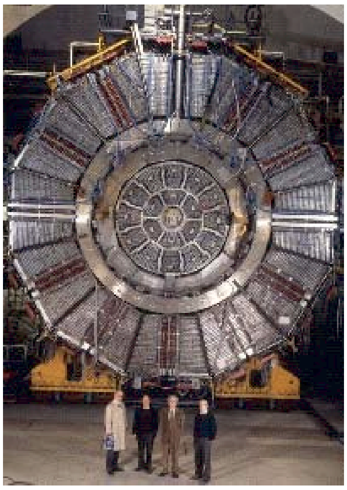


Fig. 48: The ALEPH experiment

Fig. 49: Some important actors of LEP: H. Schopper and E. Picasso (left); A. Hofmann and S. Myers with M. Bourquin, Rector of the University of Geneva and President of CERN Council (June 2001) (centre and right)

Table 3: Expected and final accuracies of various measurements at LEP

	Expected	**Final**
M_Z (MeV)	±10–15 (stat) ±17 (syst)	±2.1
Γ_Z (MeV)	±50	±2.3
Normalization	3%	< 1‰
M_W (MeV)	50–60 (stat), > 100 (syst)	ADLO: 42
$A_{FB}^{\mu\mu}$	Twice better	
τ polarization	2.5 times better	
R_b	3 to 6 times better	
A_{FB}^{b}	3 times better	