Chapter 1
The Large Hadron Collider—Background and History

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Abstract This introductory chapter gives a short account of the history of the Large Hadron Collider (LHC) project, i.e. it describes the rationale for the LHC, the situation of high energy physics in the period in which the LHC was initially conceived, and the development of the project from first ideas to first beams in the machine. In doing so, some emphasis is put on the comparison of the LHC with other pp or $p\bar{p}$ collider projects, which are also discussed from a historical point of view. Finally, the development of the LHC experimental collaborations is sketched.

1.1 The LHC—A Marvel in Every Respect

The Large Hadron Collider (LHC) is clearly a "marvel of technology".[1] The collider itself, the cryogenics installations and the experiments were all ground-breaking endeavours at the technological frontier, and the sheer size and complexity of the machines and their intrinsic beauty fascinate scientists and laypersons alike. Also the necessary civil-engineering work posed numerous awe-inspiring challenges. But the LHC is remarkable also in many other, less technical, respects:

- The LHC lifespan from first ideas to the last publication will, according to plan, amount to about six decades—enough to touch the careers of four generations of scientists.
- The number of people involved in the creation or the exploitation of the project easily reaches 10,000, and the fact that the management of the project relies chiefly on common sense and commitment without strong hierarchy and only lean formalised

[1] The excellent book of the same name edited by Evans [1] provides an abundance of useful information about the subject. A short discussion especially of the transition from LEP to LHC is provided by Schopper [2].

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responsibility sets a guiding example for other projects involving people from different backgrounds, cultures and nationalities. "The common cause seems to be a very strong motivator in keeping individual institutes on track [1]".

In order to understand and fully appreciate the immense effort that made the LHC a reality, a little digression into history is indicated.

1.1.1 The Origins of the LHC

The LHC—or the option of a hadron collider in the tunnel of the Large Electron-Positron Collider (LEP) at CERN—was reportedly first mentioned [3] by former CERN director general Sir John Adams who, in 1977, suggested that a potential LEP tunnel be made wide enough to accommodate a superconducting proton collider of above 3 TeV beam energy [4]. The late 1970 s were a period busy with exciting physics results and, at CERN, with LEP preparations. In fact, one of the arguments for a relatively large circumference for the LEP machine—which was conceived 2 years earlier, in 1975, and approved by CERN Council in 1981—was to avoid compromises to the energy of a potential hadron-collider successor of the electron-positron machine[2] [5].

By 1977, electron-positron colliders were well established, but hadron accelerators had so far exclusively been working in fixed-target mode—except for the Intersecting Storage Rings (ISR) at CERN, which, since 1971, were colliding protons with beam energies of up to 31.4 GeV (see Sect. 1.2.2).

Lepton colliders had already provided interesting results, like the co-discovery (together with a fixed-target hadron machine) of the J/ψ and thus of charm in 1974. However, the wish of particle physicists to go to ever higher centre-of-mass energies posed a severe problem to lepton colliders: The energy loss due to synchrotron radiation increases with the fourth power of a particle's energy. The fact that the energy loss per turn also scales with the inverse of the bending radius favours large accelerators—like LEP. Since there are, naturally, restrictions to the possible size of accelerators, also the achievable energy is limited for circular lepton colliders. However, the energy loss also goes with the inverse of the particle mass to the fourth power. So one way to realise collisions at higher energies is to choose protons as beam particles. Hadron colliders—so it seemed—are the only way towards the discovery of new physics phenomena at highest energies. And ideas for such new phenomena abounded already in the late 1970s!

[2] When, in 1981, the decision about location and circumference of the LEP tunnel had to be taken in the light of geologically dangerous ground beneath the Jura mountains, then CERN director general Herwig Schopper argued that the suggested smaller circumference of 22 km would make a successful *pp* collider in the LEP tunnel impossible [2].

1.1.2 The Picture of the Microcosm Around 1977

By 1977, a large fraction of what came to be known as the Standard Model (SM) of particle physics was well established.[3] At the same time, numerous questions remained unanswered, which were at the top of the research agenda of high energy physics.

- Already in the 1960s, the "zoo" of strongly interacting particles had been organised with the invention of the "eightfold way" and of quarks by Gell-Mann, Zweig, Ne'eman and others. Gell-Mann was awarded the 1969 Nobel Prize in Physics for his contributions.
- There was a model for the generation of mass for gauge bosons—the BEH mechanism invented around 1964 by Brout, Englert, Guralnik, Hagen, Higgs and Kibble, which led to the 2013 Nobel Prize in Physics for Englert and Higgs. There was, however, no direct experimental evidence of the existence of a Higgs particle that was a necessary ingredient of the theory.
- Around 1967, electroweak interactions and the BEH mechanism had been merged by Glashow, Salam and Weinberg (GSW)[4] into a renormalisable gauge theory (rewarded by the 1979 Nobel Prize in Physics). The gauge bosons of this theory ($W^{\pm}$, Z^0) were only discovered in 1983 at the Sp$\bar{\text{p}}$S—although charged-current interactions were already well established.
- The GIM mechanism (Glashow–Iliopoulos–Maiani, 1970) had postulated the existence of a fourth quark beyond the well established u, d and s quarks; the discovery of the fourth—the c or "charm"—quark through the measurement of J/ψ mesons in 1974 in both e^+e^- collisions and fixed-target experiments beautifully confirmed this hypothesis (1976 Nobel Prize for Richter and Ting).
- In 1973, the GARGAMELLE experiment at CERN had discovered neutral-current interactions in neutrino experiments, thus indirectly confirming the existence of heavy neutral gauge bosons (Z^0 bosons) as predicted by the GSW theory. GARGAMELLE also discovered that only about 50 % of the proton's momentum is carried by its charged constituents, the quarks.
- Another important discovery of the year 1973 was that of asymptotic freedom—a key ingredient of QCD—by Gross, Politzer and Wilczek (2004 Nobel Prize).
- Also in 1973, at the CERN ISR collider, high-p_T particles had been observed. This and other breakthroughs in strong-interaction physics made quantum chromodynamics (QCD), as formulated in 1973, a serious contender for a gauge theory of strong interactions. Gluons, the postulated gauge bosons of QCD, were only discovered at the PETRA e^+e^- collider at DESY in Hamburg in 1978.
- A third charged lepton, the τ lepton, was discovered in 1975 by Perl and collaborators at SPEAR (1995 Nobel Prize for Perl).

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[3] See the excellent book by Cahn and Goldhaber [6] for a historical account of particle physics.

[4] See the two articles [7, 8] for a historical perspective.

- At Fermilab in 1977, L. Lederman and collaborators obtained evidence for a fifth (the b or “beauty”) quark. The 1979 proceedings of the LEP Summer Study 1978 consequently stated that “with a little theoretical help, we can already take for granted” [9] the existence of the remaining particles of this third family (the t or “top” quark and the τ neutrino, which finally were discovered in 1995 and 2000 by the Tevatron experiments and the DONUT collaboration at Fermilab, respectively).

1.1.3 Arguments for the LHC and First Design Parameters

So there remained a lot to do before even the Standard Model would be fully established—not to talk of the many ideas about alternatives to or extensions of the Standard Model that were already around in the 1970s. At the 1984 ECFA-CERN workshop on a “Large Hadron Collider in the LEP Tunnel” [10], therefore, the main arguments for a multi-TeV hadron collider were the need to investigate the origin of mass (i.e. the role of the BEH mechanism) and to search for signs of unification beyond the Standard Model (i.e. to understand the true nature of the recently observed W and Z bosons).

Consequently, on the agenda of the LHC would be the search for the Higgs boson,[5] the understanding of the mechanism of electroweak symmetry breaking [12], the search for supersymmetry[6] “at a scale of 1 TeV, or below”, as a “necessary and sufficient condition for [...] cancellations to occur” [11], the investigation of the phenomenology of b and t quarks, and the investigation of new forms of matter and, potentially, the quark-gluon plasma [12], among others.

The tool to achieve these goals was to be a proton-proton collider[7] of centre-of-mass energy between 10 and 20 TeV (1 TeV at constituent level) and with a luminosity of up to $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. It was understood that such an ambitious machine, which was to be housed in the LEP tunnel, required an extensive R&D programme especially on the magnets, for which a maximum field strength of 10 T was assumed.

After having established the physics agenda of the LHC and its basic properties (see also Chap. 2), as perceived in the late 1970s and early 1980s, we will now turn to a discussion of pp and $p\bar{p}$ colliders that preceded the LHC or that were planned or conceived as competitors—see Fig. 1.1.

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[5] “The Higgs mechanism works, but it can hardly represent the whole truth: it’s implementation [...] is far too ugly and arbitrary” [11].

[6] It is interesting to note that in the literature of that time, there is no connection drawn between supersymmetry and the phenomenon of dark matter, the existence of which had been postulated since the 1930s.

[7] The proton-antiproton option was also studied, but it was quickly understood that the necessary luminosity would be difficult to achieve with antiproton beams.

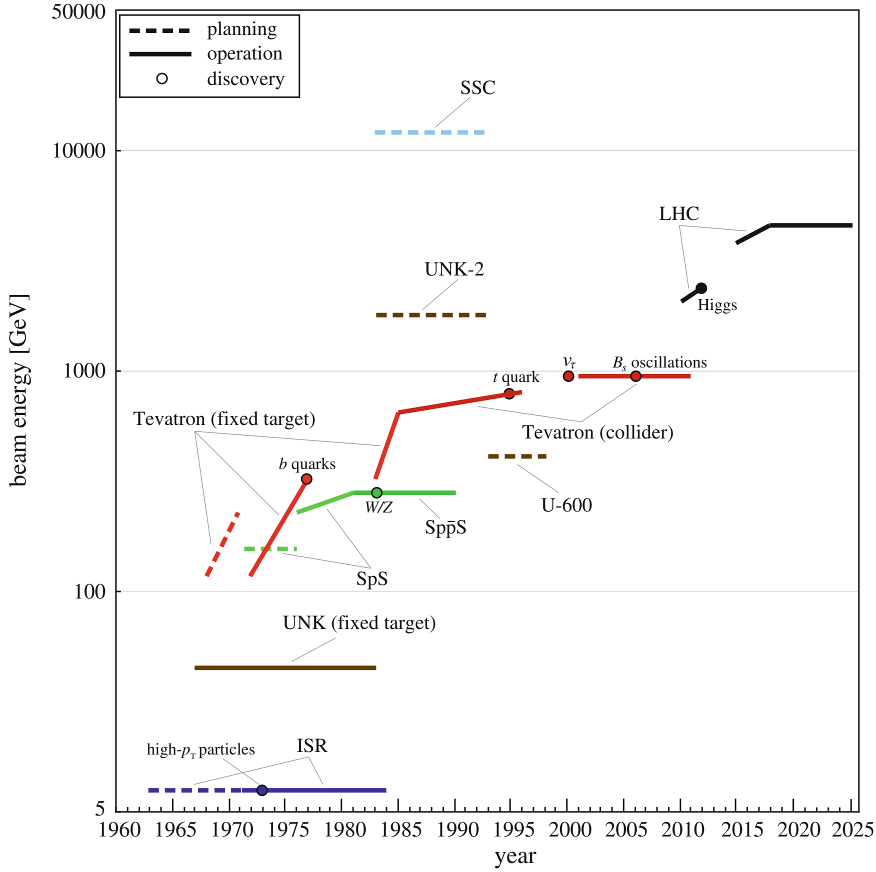

Fig. 1.1 An overview of pp and $p\bar{p}$ colliders, their beam energies and major achievements

1.2 $p\bar{p}$ and pp Colliders Before the LHC

1.2.1 Fixed-Target Experiments Versus Colliders

Fixed-target experiments had been experimenters' choice for many decades. The first mention of colliding-beam experiments is reportedly due to Wideröe who—not even working in the field of particle physics at that time—put forward the idea in 1943 and even registered a patent, which he finally received in 1953 [13, 14]. However, although people had of course realised the advantage of colliding beams with respect to fixed-target collisions in terms of usable energy, the particle densities obtained in accelerators in these day made colliders seem a very unrealistic option. This changed in 1957, when the idea of stacking particles into circular accelerators was first put forward by Kerst and collaborators [15]. Although the first thoughts about colliders

Table 1.1 Main parameters of important pp and $p\bar{p}$ colliders

	ISR	Sp$\bar{p}$S	Tevatron	UNK	SSC	LHC
Operation	1971–83	1981–89	1985–2011	–	–	Since 2008
Diameter [km]	0.3	2.2	2.18	6.61	27.7	8.49
Max. beam energy [GeV]	28/31.4	273/315 (450)	980	3000	20,000	7000
Max. luminosity [10^{30} cm^{-2} s^{-1}]	140	6	430	–	–	≈8000
Dipole strength [T]	1.2	1.3	4.2	5	6.6	8.3

focused on hadron machines, the first realisations used electrons or, later, electrons and positrons. The research on hadron machines, which posed much more severe technical problems, was, however, always continued.[8]

In the following, the relevant precursor pp and $p\bar{p}$ machines to the LHC will briefly be discussed. A comparison of a few technical numbers is given in Table 1.1; Fig. 1.2 sheds light on the physics reach (in terms of parton luminosity versus reachable energy scale) of hadron colliders operating at different centre-of-mass energies.

1.2.2 Intersecting Storage Rings (ISR, 1971–1984)

Also at CERN, colliding hadron beams were pursued. After the successful start of the CERN Proton Synchrotron (PS) in 1959, the idea of particle acceleration in the foreseen CERN hadron collider was abandoned, and conceptual work instead focused on two intersecting storage rings that could be fed by the 28 GeV proton beams of the PS.[9]

In parallel, design work for the "CERN Electron Storage and Accumulation Ring" CESAR had started in 1960, and first beams were captured in December 1963. With CESAR, many important insights into the storage and stacking of particles could be gained, so that in 1964 a proposal for the proton-proton "Intersecting Storage Rings" (ISR) was finally put forward to CERN Council and approved in December 1965; construction began in early 1966 on a site in France, just across the border from the the CERN Swiss site. In January 1969, the ISR Committee was set up; it's task was to review and select proposals for experiments to be conducted at the ISR.

The two ISR rings were ready in October 1970 and January 1971, respectively; the official inauguration of the machine (and the begin of regular operations) took place on 16 October 1971, after first collisions had already been produced on 27

[8] See the article [16] about a discussion, from 1973, of fixed target versus colliding beams.

[9] See the review article on CERN synchrotrons by Brianti [3] for more details on the CERN machines since the 1950s.

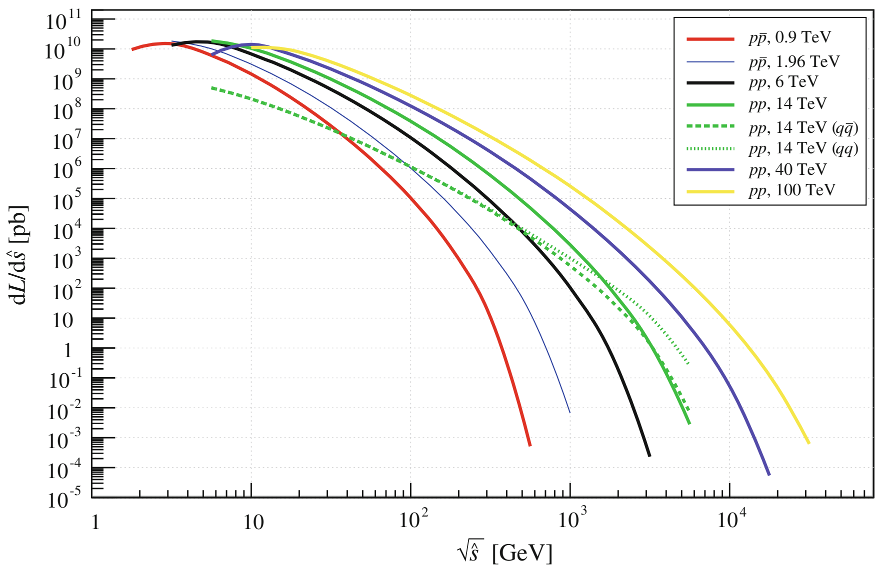

Fig. 1.2 Parton-luminosity comparisons for various pp and $p\bar{p}$ scenarios. Material from A. Cooper-Sakar

January 1971. ISR operation stopped with the dump of the last proton beams in the morning of 23 December 1983. See [17] for a thorough overview of the ISR machine and physics.

During the ISR's lifespan, important steps were taken in understanding pp colliders—among them the first tests of stochastic cooling in the first half of the 1970s (the idea of stochastic cooling had been brought forward by S. van de Meer as early as 1968). In many respects, the ISR served as a test plant for numerous concepts that were useful for all subsequent hadron colliders. "The accelerator physicists learned how to build proton storage rings that overcame the lack of synchrotron radiation damping [18]". Table 1.1 presents some of the important parameters of the ISR.

On the physics side, the experiments at the ISR—which could be set up at eight points where the counter-rotating beams crossed each other—brought many exciting insights into the physics of strong interactions [17], the most spectacular probably being the discovery of single high-p_T particles in the momentum range 2–9 GeV in 1972 [19–21] with ensuing discussions about the existence of hadronic "jets". At the time, the high-p_T phenomenon caused considerable interest because it could readily be explained in the parton model that had received support from deep-inelastic scattering experiments [22]; it was also in line with findings in e^+e^- collisions at SPEAR. However, in hadron collisions, there was, for a considerable time, no unambiguous and universally supported evidence. See [23] for a thorough discussion of the subject. A further important finding of the ISR and its experiments is the continued logarithmic rise of the pp cross section, when it was expected to flatten out at ISR energies.

1.2.3 Super Proton-Antiproton Synchrotron ($Sp\bar{p}S$, 1981–1989)

The Super Proton-Antiproton Synchrotron $Sp\bar{p}S$ was a proton-antiproton collider that built on an existing machine at CERN, the proton accelerator Super Proton Synchrotron (SPS) [24].

The SPS, of which a first design was suggested to CERN Council in 1964 as a 300 GeV machine and which was approved in 1971, had been in operation since 1976.[10] The machine could ultimately deliver proton beams of 450 GeV. For many years it served as the work horse for CERN's fixed-target physics programme.

In June 1976, three quite different proposals for proton-proton or antiproton-proton colliders had been handed in to the Fermilab Program Committee [14]. One of these proposals [25], was based on colliding beams of antiprotons and protons each at about 1 TeV. At Fermilab, none of the three proposals was immediately supported—although finally, the one by Cline and collaborators evolved into the Tevatron and the CERN $Sp\bar{p}S$. The $Sp\bar{p}S$, as detailed for the first time in [26], was designed as an extension of the existing SPS; it was intended as a tool for the search for the massive weak vector bosons that were predicted by the Glashow–Salam-Weinberg theory (and for other high-p_T phenomena, since the ISR had raised interest in high-p_T physics). The plan, however, was also criticised: In 1977, when the $Sp\bar{p}S$ was first discussed as a CERN project, the SPS—which had already been quite an expensive project—had only been in operation for a few years; at the same time the planning for a large e^+e^- collider had just started in earnest, driven by an ECFA recommendation in May 1977 to the CERN SPC that "an electron-positron storage ring of about 200 GeV c.m. energy, possibly with an initial phase of 140 GeV, be considered by the high-energy physics community as the prime candidate for a major European project in the 1980s".[11] To some, for example John Adams, trying to squeeze in the $Sp\bar{p}S$ as a slightly less expensive project seemed like asking too much from the funding agencies.

The decision to convert the SPS machine—a process requiring the first large-scale underground excavations for experiments at CERN—was nevertheless taken by CERN Council in 1979, and first collisions were observed in the experiments on 10 July 1981.

The $Sp\bar{p}S$ provided $p\bar{p}$ collisions at centre-of-mass energies of 546 and 630 GeV, mainly to the UA1 and UA2 experiments. For some exceptional runs, when the $Sp\bar{p}S$ rings were pushed to 450 GeV each, collisions could also be seen at 900 GeV. The main user of these was the UA5 experiment that, among other things, studied hadron production in high-energy collisions. UA1 recorded a few minimum-bias data during the 900 GeV runs.

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[10] The SPS first managed to deliver beams at 400 GeV on 17 June 1976, which would have been a world record had not the Tevatron achieved 500 GeV just 4 weeks before, on 14 May 1976, see Sect. 1.2.4.

[11] The same report still talks about a "hypothetical site" for LEP construction.

The Sp$\bar{p}$S had been designed and built for the discovery of the weak gauge bosons, and it fulfilled its purpose within the remarkably short time of less than 3 years: In a seminar on 20 January 1983, Rubbia (for the UA1 collaboration) and Luigi Di Lella (for UA2) presented 6 and 4 W boson candidates, respectively, and at a press conference on 25 January, the discovery of charged weak gauge bosons was announced. The discovery of the neutral boson, the Z^0, followed soon after [27–30], as did the 1984 Nobel Prize that was awarded to Rubbia and Simon van der Meer, the inventor of stochastic cooling.

Operation of the Sp$\bar{p}$S continued after the discoveries and the Nobel Prize. Among other things, the experiments were searching for top quarks and for supersymmetry. All in all, the machine was a great success, and—as Richter [14] put it—it culminated "with [...] an essential confirmation of the Standard Model. van der Meer's invention made it possible, and Rubbia's drive and determination brought it about." For a short time, in the years before the Tevatron at Fermilab resumed operations as a $p\bar{p}$ collider in 1985 (Sect. 1.2.4), the leadership in hadron collisions had been in Europe.

1.2.4 Tevatron (1983/1985–2011)

Like the Sp$\bar{p}$S, which was based on the fixed-target proton accelerator SPS, the Tevatron $p\bar{p}$ collider has its roots in a proton accelerator, the "Main Ring" of the US National Accelerator Laboratory (NAL), which today is known as Fermilab or FNAL.

The NAL Main Ring [31], designed as a proton accelerator with a maximum energy of 200 GeV, had been in construction since 3 October 1969 (informal ground breaking by NAL director R. Wilson). The final of its 1014 dipole magnets was put in place on 16 April 1971, just two and a half years later. The first proton beam was steered through the ring on 30 June 1971 and accelerated to 7 GeV, and on 1 March 1972 the design energy of 200 GeV was reached. The maximum energy of 0.5 TeV was reached on 14 May 1976. The Main Ring went out of fixed-target physics operation in mid-1982 [32]. It continued its life as injector of 150 GeV protons for the later "Energy Doubler" (or Tevatron, as especially the colliding-beam machine was called) until September 1997 [33]. A historical account of the history of the Main Ring can be found in [31]. See also [34] for a history of FNAL accelerators.

The upgrade of the Main Ring to a (in fact the world's first) superconducting machine [35, 36] with about twice the beam energy (hence the name "Energy Doubler") and subsequently to a $p\bar{p}$ colliding-beam machine [37] (the Tevatron) was approved at Fermilab in 1978, with the design goals of a centre-of-mass energy of 1.8 TeV and a luminosity of $10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The Department of Energy (DOE) authorised Fermilab to build the machine on 5 July 1979. A major milestone was reached when, on 3 July 1983, protons were accelerated to 512 GeV, which at that time constituted a new world record. In parallel to the construction of the Energy Doubler, the antiproton source was developed. Routine fixed-target operation at 400 GeV started again on 1 October 1983, and on 16 February 1984 the new record beam energy of 800 GeV was achieved. The antiproton source was commissioned in 1985, and first $p\bar{p}$ collisions were observed in the then operational parts of the CDF detector on 13 October of that year, with a centre-of-mass energy of 1600 GeV. First 900 GeV beams were produced on 21 October, and on 30 November first collisions at 1800 GeV took place. The first substantial physics run between June 1988 and June 1989 allowed CDF to collect about 5 pb^{-1} of data at 1800 TeV. Luminosity at that time was limited to about $1.6 \times 10^{30}\,\text{cm}^{-2}\,\text{s}^{-1}$.

The following years brought many improvements to core parts of the Tevatron machine, together leading to drastic increases in luminosity. During Run 1, from August 1992 to the beginning of a long shutdown in February 1996, about 180 pb^{-1} where delivered to both DØ[12] and CDF (typical peak luminosity: $1.6 \times 10^{31}\,\text{cm}^{-2}\,\text{s}^{-1}$). By then, work on the new main injector (approved in October 1991) that would replace the old Main Ring had started. The machine, which was complemented by the "Recycler" for the storage of larger stashes of antiprotons than the old antiproton accumulator could hold, was ready for physics in 1999. In 2000, the Tevatron fixed-target programme came to an end [38, 39].

Tevatron Run 2 started in 2001, then with a centre-of-mass energy of 1960 GeV, and lasted until 2011, showing peak luminosities of more than $4 \times 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$. Interestingly, the luminosity record for pp or $p\bar{p}$ colliders had been held by the ISR for around 20 years; the Tevatron took over on 16 July 2004, with more than $1 \times 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$. By the end of its life, the Tevatron had accumulated of the order of 11 fb^{-1} for both DØ and CDF. The early view on the Tevatron and a summary of its life from a machine perspective can be found in [32, 40], respectively.

From a physics point of view, the Tevatron and its predecessors at FNAL were extremely successful machines. One highlight of the fixed-target days was the discovery of b quarks by Lederman and collaborators in 1977. Others were the observation of direct CP violation by KTeV (1999) and the discovery of the last missing fermion of the Standard Model, the τ neutrino, by the DONUT experiment (2000).

The greatest success of the Tevatron, however, was the discovery of the top quark by the CDF and DØ experiments in 1995 [41, 42] and the precise determination of the mass of this last fermion of the Standard Model. After the discovery of already five quarks (until 1977) and five leptons, and after the confirmation of the Standard Model through the results of the Sp$\bar{\text{p}}$S and LEP, nobody had really doubted the existence of this particle. Indirect experimental evidence from electroweak fits, however, had hinted to a rather large mass, which meant small cross sections and difficult and time-consuming analysis.

The story of discoveries at the Tevatron did not end with the t quark: Both CDF and DØ continued to make important contributions: In 1998 the B_c meson was discovered, followed by the Σ_b baryon (with quark content uub and ddb) in 2006, the ssb baryon Ω_b (2008) and the dsb and usb Ξ_b baryons (2007, 2011). In addition, B_s oscillations were observed at the Tevatron for the first time in 2006, and in 2009, the first measurements of single top quark production were published.

[12] The DØ experiment had been operational since 1992.

The Tevatron, however, did no only succeed in the quark and hadron sector of the Standard Model—it also made important contributions to electroweak physics and beyond, e.g. by providing a very precise value for the mass of the W boson, by providing stringent limits to the mass of the Higgs boson or by narrowing down the parameter space for models of new physics.

1.2.5 UNK

The UNK was conceived in 1983 as a 21 km proton-proton storage ring at the Institute for High Energy Physics in Protvino near Serpukhov and Moscow, on a site on which since 1960 the U-70 synchrotron (in its days for some time the strongest proton synchrotron in the world) was constructed. The U-70 went into operation on 29 August 1967 and delivered beams of up to 76 GeV to numerous important experiments. Among the discoveries of the time are the phenomenon of scale invariance in hadronic interactions and the rising cross sections for collisions between pions and protons and other hadrons.

UNK aimed for two circulating beams—one of 400 GeV in a normal-conducting machine (UNK-1), and one of 3 TeV using superconducting magnets (UNK-2). Protons were to be delivered by U-70 via a 2.7 km transfer tunnel; the transfer beam line was actually commissioned in March 1994 with protons of 65 GeV. There were even ideas of porting the UA1 detector to UNK after it had fulfilled its mission by discovering the weak bosons. However, due to financial problems, already in January 1993 the focus had been shifted, by the Scientific Programme Committee of the Russian National Scientific Programme “High Energy Physics”, from the initially prioritised 3 TeV machine UNK-2 to the “earliest possible commissioning” [43] of UNK-1 with beams of up to 600 GeV (“U-600”). The work on the superconducting machine was to be kept at R&D level.

In subsequent years, civil engineering on the UNK tunnel was finalised; about a quarter of the ring is, in principal, ready for machine installation, and another half ready to be equipped with services [44]. As of 1998, about 75 % of all dipoles for U-600 were available, with many of them tested. 17 km of vacuum chamber are in store, as are many other parts necessary for building the accelerator (power supplies, RF generators, corrector magnets, etc.). In 1998, manufacturing of UNK components was stopped, and since then the tunnel and the already procured equipment are kept under more or less safe conditions.[13]

[13] The websites [45, 46] show a few impressions from the abandoned tunnel.

1.2.6 Super-Conducting Super Collider (SSC, 1983–1993)

The SSC was certainly set to "regain leadership" in high energy physics—as the US President's science advisor demanded after the W/Z boson shock [2, 5] ("Europe 3, US not even Z-Zero" [47]). The SSC was first formally discussed in the US National Reference Designs Study in 1983—the same year that also the first design ideas for the LHC were brought up [48]. Not surprisingly, the early days of the LHC were dominated by "sometimes acrimonious competition and comparison" between the two projects [5].

However, in the US, the early 1980 s were a time full of discussion about future directions, and numerous proposals for e^+e^- or $pp/p\bar{p}$ colliders were on the table [49]:

- At Brookhaven National Laboratory (BNL), there were mature plans for ISABELLE—a 800 GeV centre-of-mass energy pp collider that had been proposed in 1976, endorsed by HEPAP (the US High Energy Physics Advisory Panel) in 1977 and approved by Congress in 1978. By 1981, the tunnel for ISABELLE (later called the Colliding Beam Accelerator CBA) was essentially finished, and first beams were supposed to be possible in October 1987.
- In early 1983—just before the restart of operations of the now superconducting Tevatron —Fermilab put forward a proposal for a "Dedicated Collider" (DC) with a centre-of-mass energy of 4 TeV for $p\bar{p}$ physics, based on Tevatron technology.
- Brookhaven also considered a "Sandatron" of 10–30 TeV, with the CBA as injector.
- SLAC proposed a e^+e^- linear collider in the 1 TeV range.
- And there were first workshops for a 20 TeV proton-proton collider—later to become the SSC. At the first of these workshops, held from 28 March to 2 April 1983, also a preliminary cost estimate (without R&D, contingency, escalation etc.) of about 1.720 billion US dollar was made.

Then, later in 1983, under the impression of the discoveries at the Sp$\bar{\text{p}}$S at CERN and despite the enormous costs (which triggered many heated discussions in the US), the responsible HEPAP Subpanel on New Facilities for the US High Energy Physics Program recommended "the immediate initiation of a multi-TeV high luminosity proton-proton collider". It also stated that it recommends "Fermilab not proceed at this time with the Dedicated Collider" and that "the [CBA] project at Brookhaven not be approved[14]" [50]. The recommendations were endorsed by HEPAP, and first funds for preliminary SSC studies were transferred from CBA. A study, completed in 1984, estimated the total costs of the collider complex to be of the order of 3–4 billion dollar.

The SSC plan was quite daring: The parameters foreseen in 1984 by the Central Design Group suggested building a pp collider of 20 TeV beam energy with a luminosity of 10^{33} cm^{-2} s^{-1} and six experimental areas. A conceptual design report with these benchmarks was delivered to the DOE on 1 April 1986. On 30 January 1987,

[14] Today, the tunnel constructed for ISABELLE houses the heavy-ion collider RHIC.

President Reagan approved the SSC at a total cost estimate of 4.4 billion dollar, and first funds (still dedicated to R&D, since the funding situation in the US was not easy) were provided by Congress in 1988.

The SSC site selection was a delicate process during which important political supporters of the SSC were turned into opponents of the project—a fact with "long-range repercussions" [49]. Initially 45 site proposals were submitted, out of which seven sites were considered to meet all selection criteria. These were ranked, and on 18 January 1989, it was finally decided to site the SSC in Texas.

The building-up of the SSC Laboratory (SSCL) and the construction of the machine could start after first construction funds had been approved by Congress in autumn 1989. In parallel to these activities, a site-specific design report was prepared, which (involving external expertise) in July 1990 led to a new cost estimate of 8.6 billion dollar. Ideas were circulated to decrease the centre-of-mass energy as the only means to significantly reduce costs, but they were refuted with the argument that the physics potential would be seriously compromised [51]. A report by a DOE committee delivered in August 1993 led to the "claim that the SSCL costs went up to over" 11 billion dollar [49]; in addition it was reported that most technical systems were late by up to 1 year and that the magnet construction posed a serious cost risk. These developments finally, after significant political "roller-coaster" [49], led to the termination of the SSC project by the US Houses in October 1993. By then, about 2 billion dollar had been spent, and 23.5 km of SSC tunnel had been constructed. 640 million dollar were approved for termination costs of the project. In the end, the close-out of the SSCL took 2 years and cost 736 million dollar. In 1994, the responsible HEPAP subpanel recommended US participation in and contribution to the LHC [52].

The reasons for the failure of the SSC project have been discussed in many places. The sheer size and cost of the project were problematic—the LHC, relying on existing infrastructure like the LEP tunnel and a system of pre-accelerators, had a clear advantage in this respect; and the fact that the LHC allegedly could be realised at significantly lower costs certainly was a serious (psychological) burden for the SSC.[15] Also the strong increase in the project costs from start (1,72 billion US dollar for the accelerator complex) to end (11 billion dollar total project costs) was a problem, not least because it was taken as further evidence for the bad management of the project.

Also the physics potential of the SSC—in comparison to the LHC—was an issue: The design centre-of-mass energies differed by a factor of almost 3—but the design luminosity of the LHC was a factor of 10 higher than that of the SSC, making the LHC competitive for almost all relevant processes (see the discussion in the next section) and thus weakening the SSC physics case.

Finally, international collaboration was heavily debated during SSC planning: The SSC was designed to "restore US pre-eminence" in high energy physics [49],

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[15] Note, however, that the cost estimates for building the SSC close to Fermilab, and thus using the Tevatron and its facilities as injector, were, according to most sources, not significantly lower than for the Texas site.

a fact which at first sight precluded international contributions to the project.[16] Nevertheless, various models for international collaboration were discussed, ranging from the usual model of commonly operated experiments over what later became to be known as the "HERA model" (in which roughly 20 % by cost of the accelerator's components had been produced by countries other than Germany) up to a purely financial involvement in SSC construction. The focus later was on international involvement in all R&D aspects, with purely national SSC construction, also because there were strong opinions against (in-kind) contributions that ostensibly would transfer US jobs to abroad. Still, many connections on laboratory and also government level were established between the USA and other countries; in the end they led to nothing, also because the new Clinton administration that stepped into office in January 1993 ordered a "go slow" policy and planned for a 3 year delay in the completion of the machine [51]. This, in turn, discouraged foreign partners: "Major foreign participation has remained elusive because of uncertainty about the US commitment to the project, yet our own commitment has wavered in large part because of the absence of foreign funding" [51].

All in all, the SSC probably did not seem very inviting to other nations ("The President has decided to build such a machine and you have the option to join the project or leave it." [2]), and when later the SSC went into serious funding problems and other nations were asked to contribute at the billion-dollar level, this attitude was well remembered [5].

1.3 LHC Development and Timelines

1.3.1 From First Ideas to First Approval

As described above, the possibility of a hadron collider in the LEP tunnel was first mentioned in the notebook of John Adams. Serious discussions of a large proton collider started with the first internal notes in 1983 [48] and the first CERN–ECFA workshop in March 1984 [53], under CERN director general Herwig Schopper. The 1984 workshop clearly was a reaction to the developments in the US, where the SSC project was maturing quickly after the $W^{\pm}/Z^0$ shock. And already in May 1984, Schopper presented plans to the meeting of the AAAS, the American Association for the Advancement of Science, to build a superconducting proton collider with 5 TeV beam energy on top of the LEP magnets. A price of only 500 million US dollar was mentioned [49], and the existing LEP tunnel was introduced as a decisive advantage in terms of cost and time for the LHC over the SSC.

[16] As an example, in the site-selection process, a proposal locating the SSC across the US–Canadian border was rejected partly because of its not being fully national.

Wrong as the absolute numbers may have been (see Sect. 1.3.4 for a discussion of LHC costs), the tone for the ensuing competition between SSC and LHC was set: The LHC might be realised faster and cheaper than the SSC (there were initial estimates of the cost relation between SSC and LHC as high as 3:1 or higher); the LHC might even be regarded as an intermediate project before the realisation of the SSC. The SSC, on the other hand, claimed a clear physics advantage on the grounds of the significantly higher centre-of-mass energy. To this, CERN again reacted by pointing out the higher LHC luminosity (after careful studies of the magnet potential, the design value had been changed to $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$).[17]

For physical reasons, any new proton-proton collider was required to achieve collisions with centre-of-mass energies, at the constituent level, of at least 1 TeV. Taking this energy as a reference, Fig. 1.2 shows that indeed the LHC, with a ten times higher luminosity compared to the SSC, has similar parton luminosities both for gluon-gluon induced processes and for those induced by quark-antiquark pairs. The plot shows, as a function of $\sqrt{\hat{s}} = \sqrt{s \cdot x_1 \cdot x_2}$, the gluon-gluon parton luminosity $\frac{\mathrm{d}L}{\mathrm{d}\sqrt{\hat{s}}}$ for proton-proton collisions at different centre-of-mass energies. For the LHC design energy of 14 TeV also the quark-antiquark and quark-quark parton luminosities are shown.[18] The LHC can even compete with the SSC for slightly higher energy scales, up to maybe 5 TeV. The higher centre-of-mass energy of the SSC clearly becomes relevant for the highest scales of 10 TeV where, however, the overall statistics for any rare process will be tiny even at the SSC.[19]

The next years were very eventful: In 1985, a “Long-Range Planning Committee” (LRPC) was installed at CERN, chaired by Carlo Rubbia. 1987 was a particularly eventful year: In January, US President Reagan approved the SSC—a step that very much put the LHC project in doubt.[20] A second general workshop on the “Physics at Future Accelerators” was held in La Thuile, at which the three subpanels of the LRPC discussed their findings [54]; they supposed the LHC to have realisable luminosities between 10^{33} and $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and a maximum beam energy of 8 TeV. This idea was put to CERN Council in 1987, together with an R&D programme for the 10 T dipole magnets, which was started soon after. In 1987, finally, also the Texas site was selected for the SSC.

In 1989, Rubbia became CERN director general. Since the beginning of his mandate, his line of argument for the LHC was fixed (see for example his presentation

[17] It is interesting to read, in parallel, accounts of the SSC–LHC competition written by SSC advocates [49] and by LHC supporters [2]. Even when talking about the same events, e.g. a US Congress hearing in April 1987, they seem to be telling rather different stories. Especially the evaluation of efforts for international collaboration on the SSC is very different—even in texts written 15 years after SSC cancellation.

[18] The quark-quark parton luminosity here is obtained by using the quark-antiquark parton luminosity for $p\bar{p}$ collisions.

[19] Note that, due to the large total proton-proton cross section, luminosities beyond values of around $10^{36}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ do not result in an increased physics potential, but only in massively reduced beam lifetimes.

[20] “It was only the resilience and conviction of Carlo Rubbia [...] that kept the project alive” [18].

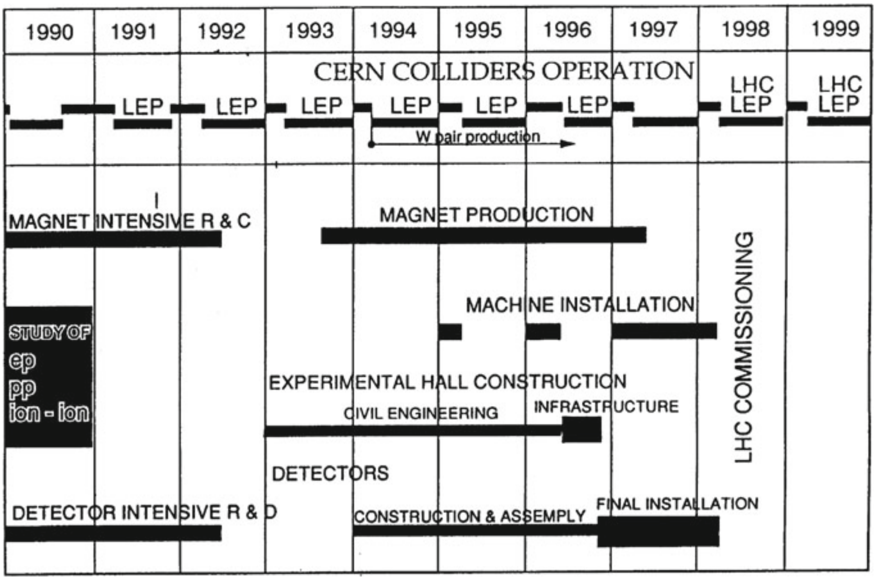

Fig. 1.3 LHC construction schedule, as proposed by Rubbia in 1990. Adapted from [12]

to the fourth general "Large Hadron Collider Workshop" held in Aachen, Germany, in 1990 [12]):

- Hadron collisions at the "energy frontier" and with a constituent-level centre-of-mass energy of 1 TeV are the correct approach to finding new, interesting physics.
- The LHC is healthy competition for the SSC, at moderate cost and an advantageous timescale.
- Because of the possibility of a heavy-ion programme and the potential to have concurrent running with LEP and thus also the *ep* option, the LHC is much more versatile than SSC.[21]
- The LHC disadvantage in centre-of-mass energy was, by Rubbia, seen as compensated by its higher luminosity.

Rubbia, at the 1990 workshop, announced the goal of having the first full LHC magnet string ready by 1992. The machine parameters he presented then suggested a beam energy of 7.7 TeV, a maximum luminosity of up to $5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and—very optimistically—first operations in 1998 (see the timeline plot in Fig. 1.3)!

[21] Note that in the La Thuile workshop [54] even the possibility of also having $p\bar{p}$ collisions—at much reduced luminosity—in the LHC is mentioned. Also, from very early days of LHC discussions on, the complementarity of "high-precision" e^+e^- instruments like LEP and of "high-energy" machines like the LHC has been stressed [12]. In Aachen, Rubbia also discussed the necessity of linear e^+e^- colliders "such as CLIC": "In particular the LHC has to be conceived as a machine precursory to CLIC [...] As often in the past a first 'exploratory' phase with hadron collisions is necessary precursory to the second 'consolidating' phase using electrons and positrons".

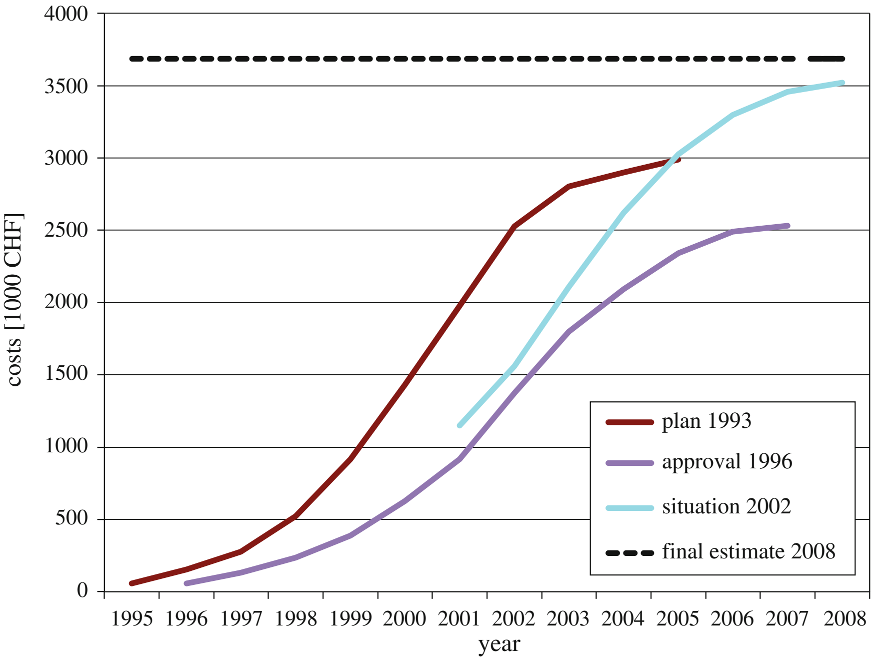

Fig. 1.4 LHC funding scenarios at different stages of the project. *Source* CERN

Then, in 1991, the LHC started its way through the CERN approval procedure: In December, the LHC was first presented in detail to CERN Council, and Council adopted the project, recognising the LHC as "the right machine for the advance of the subject and the future of CERN". Rubbia was asked to prepare a full proposal, including a cost estimate, by the end of 1993 [5]. In early 1993—when, in the light not only of the SSC developments, the LHC did not seem "inevitable" [4]—Rubbia handed over the responsibility for producing a complete proposal to the designated next director general, Chris Llewellyn-Smith. Prospects then were not encouraging: "[...] costing was significantly bigger than previous estimates [...]; attitudes towards high-energy physics were hardening in several CERN member states; and the CERN Council had just agreed to a temporary reduction in Germany's contribution on the grounds that reunification was proving very costly" [5].

In October 1993, the SSC was cancelled. Llewellyn-Smith later wrote that "I do not think that the LHC would have been approved if the SSC had not been cancelled [...]" [4]. In December 1993, Llewellyn-Smith presented his proposal for the LHC to CERN Council, based on a two-in-one machine (see Chap. 2 for technical details) installed above the LEP accelerator[22] and to be commissioned in 2002. The overall proposed budget (see Fig. 1.4) relied on a mixture of a general budget

[22] This idea was only given up in 1995, when it was decided to dismantle LEP in order to gain space for the LHC. However, nobody had really pursued the idea of *ep* physics in the LEP/LHC tunnel seriously.

increase for CERN, additional voluntary contributions from some member states and contributions from non-member states. Council asked the CERN management to further reduce the costs,[23] and proposals were developed to further delay the machine commissioning by 1 or 2 years and to reduce all other CERN activities (except the CERN flagship LEP) to an absolute minimum.

In the meantime, the LHC received (moral) support from other sources: After the cancellation of the SSC, the HEPAP in the US suggested to join the LHC, and ICFA issued a supportive statement for the LHC, which they considered to be “the correct next step for particle physics” [4].

In June 1994, approval was requested from CERN Council for a machine of 14 TeV centre-of-mass energy with luminosity up to $10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. The cost for the machine was given as 2230 million swiss francs (MCHF) [55]. Additional costs for the experimental areas were stated as 210 MCHF, and CERN’s contributions to the experiments as 220 MCHF. The vote on the proposal and in fact the Council meeting itself were, for the first time in Council history, left open because it was clear that the UK and Germany would not have accepted the plan; the two countries demanded further voluntary contributions from France and Switzerland who, in their view, as host states profited very much from the LHC.

Difficult political discussions followed, during which e.g. France and Switzerland agreed to extra contributions by providing a 2 % inflation adjustment (compared to 1 % for all other member states), and in December 1994, CERN Council approved a two-stage procedure for LHC construction [56]: A “missing-magnet” machine that left out one third of all magnets was to be constructed for commissioning in 2002 and operations at 9–10 TeV centre-of-mass energy in 2004, with an upgrade to 14 TeV envisaged for 2008. The plan saved about 300 MCHF in direct construction costs for the first stage; the staged approach, however, came with additional managerial and other costs, so that the net effect was unclear. The plan was to be reviewed latest in 1997 on the grounds of additional non-member state funds (which were to be used not to reduce member state contributions, but to speed up the project), and depending on the budget conditions required by the UK and Germany, including the contribution rebate that Germany had received on the grounds of the expensive reunification.

1.3.2 From First Approval to First Beams

In the following 2 years, several non-member states became observers to the LHC project: Japan, India and Russia; in December 1997, also an agreement about LHC contributions could be signed with the USA. Also Canada promised substantial contributions to the LHC. These developments made the CERN management confident that a single-stage machine was still possible. Then, quite unexpectedly, Germany announced their intention to reduce CERN contributions (and in fact all international

[23] In fact, mainly the UK and Germany opposed the plan and even managed to get the voting procedures in Council changed to a scheme that favoured the larger contributors.

scientific contributions) by around 9 %. The UK chimed in. The US agreement was not yet signed at this point, and CERN felt quite anxious that the German and UK plans might scare away the non-member states, which had been assured that their contributions would not be used to reduce the contributions of the member states.

In the following discussions (see Llewellyn-Smith's vivid account of the time [4]), there were rumours of Germany and UK even wanting to leave CERN; on the other hand CERN made it clear that the suggested budget cuts would kill the LHC project. The solution that was found was unique for scientific projects: It was decided that CERN was to be allowed to take out loans (the German statement was that "a greater degree of risk would inevitably have to accompany the LHC"). With this risky solution, LHC construction in a single stage (a necessary condition to keep the non-member states on board) was approved by CERN Council in December 1997 [57], with commissioning at full energy foreseen for 2005, the start of operations in 2006 and design performance in 2007. The corresponding budget cuts were marginally smaller than demanded by Germany, and in addition a 1 year "crisis-levy" on all CERN salaries was imposed. The plan was to be reviewed half-way.

So in late 1997, the LHC was approved—but, as Lyn Evans, then LHC Project Leader, says [18]: "With all contingency removed, it was inevitable that a financial crisis would occur at some time, and this was indeed the case when the cost estimate was revised upwards by 18 % in 2001." "[...] the budgetary position was extremely fragile. The deficit financing of the LHC was hyper-sensitive to small changes in the timing of the contracts" [5].

In 2001, it was communicated by CERN management that the LHC would become significantly more expensive than expected (see above), a statement that came as a shock to the public and was not well prepared. The main drivers of this increase were the dipole magnets and the necessary erection of a second cryogenics line. The solution to this problem—which "should [...] not have been a surprise" [5]—was to increase the level of borrowing and to further extend the construction period "which was necessary anyway on technical grounds for both the machine and the detectors" [18]. The rest of the story is quickly told (and told in more detail in Chap. 2 and in [1]): LHC was commissioned in 2008, with first beams travelling around the machine on 10 September, producing beam-splash and beam-gas events.

1.3.3 Evolution of High Energy Physics Since 1977

When first physics collisions were recorded in the LHC experiments, the world of high energy physics had changed (if only slightly) with respect to 1977, when the LHC was first mentioned (see Sect. 1.1.2):

- LEP, Tevatron, HERA, the B factories and many other facilities and experiments had convinced us that the Standard Model works extremely well at the one-loop level. Furthermore, it had become clear that, if nature were supersymmetric, the gauge couplings of the three gauge groups forming the Standard Model would unify at very high energy scales, thus sharpening the case for searches for supersymmetric extensions of and new physics beyond the Standard Model.

- With the top quark and the τ neutrino, the last two fermions of the Standard Model had been discovered. The very large top-quark mass opened room for speculations about new physics phenomena in a regime that LHC, with its high energy and high luminosity, could cover exceedingly well.
- LEP had demonstrated that there are only three light neutrinos; furthermore it had been learned that neutrinos had small, but non-zero masses.
- The scientific case for SUSY had further sharpened through its natural connection with dark matter, which, initially, had not been part of the case for the LHC.
- However, supersymmetry or other extensions of the Standard Model, and also the Higgs boson of the Standard Model had not yet been discovered—so that even after more than 20 years after the first outline of the LHC physics menue this menue was still valid!
- Observations of small deviations between Standard Model predictions and measurements—i.e. of B decays, of $(g-2)_{mu}$ or of the effective electroweak mixing angle—are not necessarily significant; but they do raise considerable interest and are, partly, open for scrutiny at the LHC.
- On the experimental side, the largest steps forward had been in tracking detectors. First medium-scale semiconductor detectors had already been in use in the LEP experiments and at the Tevatron (for the top-quark discovery!) for secondary vertexing. However, at the time of John Adams nobody would have dreamt of building a radiation-hard all-silicon tracker with an area the size of a tennis court and some 76 million channels!

So, all in all, during the more than 30 years between the first ideas about LHC in 1977 and the start of operation, only small changes to the objectives of the LHC had become necessary.

1.3.4 LHC Funding and Construction Timelines

As has become clear, the genesis of the LHC was a complex story—also politically and financially. It is not easy to summarise the costs of the LHC and to follow the funding proposals over the years between first plan (December 1993) and commissioning (2008). This difficulty is due to several effects:

- Firstly, the numbers from different years often refer to price levels of different years, i.e. they are not always corrected for inflation effects.
- Secondly, the definition of the LHC project costs varied. A few examples: inclusion of personnel or not; inclusion of generic R&D costs; inclusion of test and pre-operation costs; inclusion of in-kind contributions; inclusion of escalation etc. In the following, only material costs to completion will be discussed—which will lead to differences to the numbers specified in the text in Sects. 1.3.1 and 1.3.2. The numbers quoted below include the machine and tunnel construction,

the construction of the experimental areas and, at least for the later years, also in-kind contributions, machine R&D, tests and pre-operations.

- Thirdly, the accounting schemes at CERN underwent significant changes over the years.

For all these reasons, the numbers given below (and also above in the text) and also in Fig. 1.4 have to be taken with great care. Figure 1.4 shows the following funding profiles for the LHC:

- the December 1993 plan with commissioning foreseen for 2002. The total material costs were given as 2988 MCHF (in 1993 prices);
- the budget plan approved in 1996 which—after having collected sufficiently many non-memberstate contributions and after having economised on the CERN programme—foresaw commissioning at full energy in 2005. This plan included reductions due to more economies on the CERN side and a stretched schedule;
- the budget estimate from 2002 that was developed after the increase in cost had come to light in 2001. With respect to the 1996 plan (which in 2001 had already been significantly violated), a materials cost increase of around 1150 MCHF can be inferred (see the comments below);
- the final 2008 materials cost sum. Not included in the discussion here are costs for repair after the 2009 incidence (see Sect. 2.3.4) and for increased quality control and monitoring etc.

Difficult as a direct comparison of the various scenarios may be, it is worth looking a bit closer at the approved number from 1996 (2530 MCHF) and the 2008 cost of the project (3685 MCHF). The first of these numbers is given in 1996 prices, i.e. assuming (completely unrealistically) no inflation. The 2008 number, in contrast, is given in actual costs. Assuming an average annual indexation on materials costs of 2 %, the 1996 number would already become over 3200 MCHF, leaving a gap of under half a billion MCHF and thus representing a cost increase of roughly 13 %. The author is tempted to say "only" 13 % since—as a brief look at current large-scale public projects easily shows—budget overruns of even several 100 % seem not to be the exception but rather the silently accepted rule. As Llewellyn-Smith [5] cites from a 2003 "The Times" supplement: "If those involved didn't lie about the cost, they [the large construction projects (ed.)] would never be built."

So, all in all, it seems fair to say that—for a project of this size and complexity, and for a project that basically was approved before the necessary R&D was completed–the LHC stuck remarkably well to schedule and budget. This is particularly notable since at the time of approval, many future developments were not yet foreseeable (e.g. exchange rates, inflation, etc.). Figure 1.3 shows Rubbia's 1990 expectation that—with civil engineering starting in 1993—first beams should be delivered after 5 years, in 1998. In fact, civil engineering started in 2000, and first beams entered the machine after 8 years, in September 2008 (see Sect. 2.3.3).

1.4 Superconducting Magnets for Particle Physics

The history of superconducting (SC) magnets for particle accelerators [58, 59] begins in the 1960s, when first R&D programmes were started. A first collaborative effort aimed at providing SC magnets for the SPS (Sect. 1.2.3) was, however, abandoned because of technical problems, and the SPS became a machine with resistive magnets (commissioned in 1976). At CERN, the SC idea was further pursued for the ISR which received, in 1980, powerful SC quadrupoles as part of a luminosity increase.

The SC magnet story was continued by efforts towards increasing the energy of the NAL Main Ring (Sect. 1.2.4), and towards the design of the ISABELLE or CBA 4–5 T dipole magnets (Sect. 1.2.6). The development of the latter, after a promising start, proved more complicated and time-consuming than initially expected, and after the discovery of the weak bosons at the Sp$\bar{p}$S and the progress in the Tevatron programme, CBA was considered superfluous and finally abandoned.

At the Tevatron, thanks to the new superconducting magnets of 4.2 T, in 1983 a new energy world record was reached, with a beam energy of 512 GeV. The Tevatron magnet design still had a warm return yoke—in contrast to ISABELLE, where the yoke would have been part of the cold mass kept at 4.2 K. A big advantage of the Tevatron magnets—and a concept that from then one became integral part of all SC accelerator dipole magnets—was the "collar system" that helped to contain the radial forces exerted by the electromagnet fields on the coils. A further ingenious achievement was the acceleration of both protons and antiprotons in one common beampipe, which saved a second magnet ring. All in all, the Tevatron used more than 700 SC dipole magnets.

The proton ring of the HERA electron-proton collider was developed in the 1980s. Similar in size to the Tevatron ring (see Table 1.1), it was based on a few conceptual improvements: The two most important ones were probably that, first, the iron of the return yoke was integrated into the cold mass—a solution that avoids problems concerning coil centering and alignment. Second, the approximately 500 5.5 T SC magnets for the HERA ring were produced by industry and not manufactured at the laboratory. This led to a significant cost reduction.

Also the SC magnets for the heavy-ion collider RHIC—which was under constant financial pressure—were to a large extent produced by industry. RHIC profited from experience gained earlier at other machines—also in the development of the magnets of the SSC, which was to be built in parallel. SSC was a "leading project for SCM development, backed by a joint effort of all major US laboratories" [58]. Numerous studies had led to the final design of the SSC magnets for 6.6 T at 4.4 K, necessary to meet the design goal of 20 TeV beams. Also SSC foresaw steel collars and cold iron. Among the many key developments for the SSC was that of new SC cables that showed a very high critical current. However, some technology choices of the SSC showed to not have been optimal. One drawback—also in comparison to the LHC design—was the use of single-bore magnets that necessitated the construction of two separate rings. Others were the ambitious choice of the working point and a later increase of the bore.

The history and design of the LHC magnets is documented in many places (see e.g. [1]). The LHC, relying substantially on previous R&D, took a few innovative design choices (two-in-one magnets, cooling to 1.9K and thus work with superfluid helium) and "pushed the $NbTi$ technology to its extreme" [1], finally resulting in the known dipole fields of 8.3T.

1.5 Forming the Collaborations

One of the first large-scale dedicated meetings for LHC detectors[24] was an ECFA "Study Week on Instrumentation Technology for High-Luminosity Hadron Colliders" in Barcelona in 1989 [62, 63]. Here, also the first precursor of experimental collaborations—EAGLE ("Experiment for Accurate Gamma, Lepton and Energy measurements")—started forming.

The next important step was the 1992 CERN–ECFA workshop "Towards the LHC Experimental Programme" in Evian [64]. It took place soon after CERN Council's unanimous December 1991 vote that the LHC is "the right machine for the advance of the subject and for the future of CERN" [5]. During this workshop, proto-collaborations presented "expressions of interest" describing the respective detector plans. The interest in contributing to the LHC experimental programme was large: all in all, 12 proposals were made in Evian:

- There were four proposals for general-purpose experiments: EAGLE, ASCOT ("Apparatus with SuperCOnducting Toroids"), CMS ("Compact Muon Solenoid") and L3+1 (or L3P, an upgrade of the L3 LEP experiment for the LHC).
- Three *b* physics experiments entered into the competition for approval. One concept was based on *pp* collisions in the LHC ("COBEX"); a group which called themselves the "LHB collaboration" would use a beam extracted from the LHC by crystal channeling for fixed-target operation; the third wanted to use a gas-jet target for the proton beam in one of the straight LHC sections ("GAJET").
- Similarly, three proposals were made for heavy-ion experiments; the one later called ALICE; one that wanted to use the DELPHI detector from LEP, and one that suggested a heavy-ion programme for the CMS detector.
- In addition there were two proposals for neutrino experiments, one brought in by the NOMAD collaboration.

It was probably clear from the beginning that only two general-purpose experiments would be accepted at the LHC, one of them potentially being a toroidal apparatus like ASCOT and EAGLE. Therefore, these two proto-collaborations, in a voluntary move, merged to form the new ATLAS ("A Toroidal LHC ApparatuS") collaboration in spring 1992. Over the summer of 1992, the ATLAS, CMS and L3+1

[24] Detailed technical discussions of the existing large LHC experiments can be found in Chap. 3. An overview of the organisation, funding and management of large collaborations can be found in [60, 61].

collaborations wrote "Letters of Intent" (LoIs) that, on 1 October 1992, were handed in to the newly formed CERN LHC Experiments Committee (LHCC) [1, 65, 66].

Among the remaining three general-purpose experiments, ATLAS and CMS were invited to provide [67] detailed technical proposals, which they did in 1994. CMS and ATLAS were finally approved in January 1996, and "green light" for construction was given on 31 January 1997, with an expenditure ceiling of 475 MCHF (1995 currency rate). In fact, up to the LHC start of operation, the requested funding of ATLAS and CMS amounted to 540.9 and 566.3 MCHF, respectively [60], meaning rather moderate cost overruns.[25] Construction started in 1997, the ATLAS cavern was inaugurated on 4 June 2003, and the last large pieces of ATLAS and CMS were lowered into the experimental caverns on 29 February and 23 July 2008, respectively.

The situation for the b physics experiments was slightly more involved: COBEX, GAJET and LHB submitted LoIs in October 1993. At that time, the new B factories at SLAC and KEK were already under construction. However, the LHCC came to the conclusion that the large data statistics available at the LHC would allow a dedicated experiment to gain physics results beyond what was possible at the factories. Therefore, it was recommended in January 1994 to foresee a dedicated b physics experiment at the LHC, and the LHCC asked the three submitters to form a single collaboration, based on the collider-mode suggestion. In February 1998, the newly formed LHCb collaboration submitted a technical proposal, and in September 1998 it was accepted.

The ALICE LoI was submitted in March 1993, the technical proposal followed in 1996, and the experiment was approved in February 1997. The DELPHI proposal was turned down.

The four big experiments ALICE, ATLAS, CMS and LHCb were followed by three smaller, more focused proposals for experiments: The TOTEM experiment (LoI 1997) is investigating the total pp cross section, elastic pp scattering and diffraction dissociation; MoEDAL (LoI 1998) is searching for magnetic monopoles and other exotic phenomena; LHCf (LoI 2003), finally, uses very forward particles created in LHC's pp collisions to simulate cosmic rays.

1.6 Conclusion

The history of the LHC cannot be told without telling the history of other collider projects and—in fact—of the greatest part of particle physics in the last five or six decades. Beyond the obvious topics in the field of collider physics, many aspects would have to be discussed: politics, finance, sociology, management. The full history of our field, seen from these points of view, still needs to be written.

[25] These numbers do not contain the extraordinary efforts from laboratories and universities around that world that contributed to the experiments using national funding sources.

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