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Introduction and overview

1.1 Elementary particle physics

Elementary particle physics is the study of the fundamental constituents of matter and the forces between them. It is also called High Energy Physics (HEP) because in order to study fundamental particles with smaller and smaller sizes, shorter and shorter wavelength probes are required which correspond to higher and higher energy.

The field of high energy physics has proceeded for the past ~60 years in a typical sequence: a new accelerator opened up a new range of available energy (or type of accelerated particle, e.g. colliding beams of positrons and electrons), and coupled with new detector technology – which enabled improved or previously impossible measurements to be made – rapidly yielded discoveries soon after it started up. The hadron accelerators which have had the most influential impact on the modern high energy particle and heavy ion physics discussed in this book are shown in Figure 1.1. The upper branch shows four major generations of p–$p(\overline{p})$ colliders starting from the CERN Intersecting Storage Rings (ISR), the first hadron collider, while the lower branch depicts the major heavy ion facilities in the USA and Europe. The AGS at Brookhaven National Laboratory (BNL) ran for p–p physics from 1960–2002 and is now the injector to RHIC. The fixed target p–p programs of Fermilab (1972–) and the CERN-SPS (1976–) are also not shown. The CERN-SPS fixed target light ion program started in the same year (1986) as that at the AGS, but is plotted starting in 1994 when Pb beams were first provided.

1.2 The fundamental constituents of matter and their interactions

In brief, the properties of elementary particles must be conserved when they interact with each other. This leads to the study and classification of interactions according to conservation laws. The properties must be intrinsic properties of the

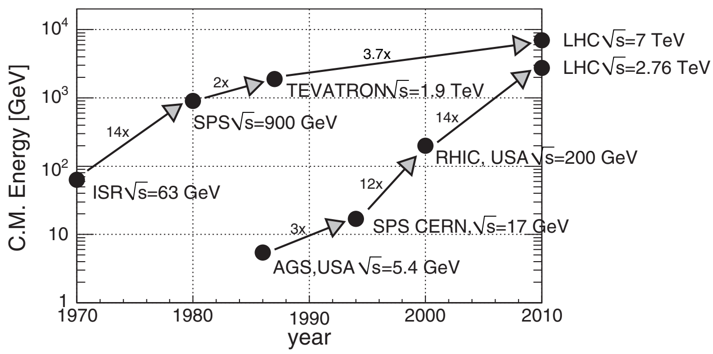

Figure 1.1 Most influential accelerators for high p_T p–$p(\overline{p})$ and heavy ion physics with their starting dates (dots) for the relevant activity.

particle itself and not just of a particular frame of reference. This leads to the study of invariance and symmetry principles. For instance, all the interactions (or forces) of nature conserve energy ($E = Mc^2$), a scalar; momentum ($\mathbf{p} = M\mathbf{v}$), a vector; and angular momentum, a vector ($\mathbf{L} = \mathsf{I} \cdot \boldsymbol{\omega}$), which may be in a different direction than the angular velocity vector $\boldsymbol{\omega}$ due to the inertia tensor, I; here M is the relativistic mass of a particle, $\mathbf{v}$ its velocity and c is the speed of light in vacuum. The relativistic formulas are used since high energies imply relativistic velocities. It is important to note that the relativistic mass of a particle is not an intrinsic property of a particle since it is frame dependent. This leads to the concept of invariant mass or rest mass (m) of a particle, where $mc^2 = \sqrt{E^2 - (pc)^2}$ is the invariant mass of the particle, which does not depend on the particle velocity $\mathbf{v}$ and is the same as the mass of the particle measured in its rest frame.

The properties by which elementary particles are classified are the following:

(i) rest mass, m, where mc^2 is measured in units of electronvolts ($1\,\text{eV} = 1.6 \times 10^{-19}$ J), or million electronvolts (MeV), etc.,

(ii) spin, which is the intrinsic angular momentum of a particle as seen in its rest frame in units of Planck's constant ($\hbar = 6.6 \times 10^{-16}$ eV s),

(iii) interaction strength for the fundamental interactions, for example electric charge in units of the proton charge ($e = 1.6 \times 10^{-19}$ C),

(iv) symmetry properties – these are observed symmetries which are not necessarily understood and sometimes lead to grouping of elementary particles in multiplets.

From now on, we shall use the standard units of HEP, with $\hbar = c = 1$, $\alpha \equiv e^2/(\hbar c) \simeq 1/137$.

At our present state of knowledge there are four fundamental forces of nature: gravity, electromagnetism, the weak interaction responsible for radioactive decay and the strong interaction or nuclear force which binds nuclei. In quantum field theory, forces correspond to the exchange of fundamental objects or quanta, with the "range" or effective distance over which the force acts being inversely proportional to the rest mass of its quantum. The quanta of all known forces have integer spin and are called bosons; the sources of the forces are fundamental particles with "charge," which have half-integer spin and are called fermions. The designations fermion and boson relate to the Fermi–Dirac or Bose–Einstein "statistics" of the particle, a property of the quantum mechanical wave function. Bosons have symmetric wave functions, while fermions have anti-symmetric wave functions which leads to the Pauli exclusion principle [6–8].

The quantum of electromagnetism is the photon, which itself has zero electric charge, so that photons do not interact directly with each other. The photon has zero rest mass which means that the range of electromagnetism is effectively infinite. The force of electromagnetism operates by the exchange of virtual photons from particles with electric charge, for example electrons. The word "virtual" means that the particle is off its mass shell, i.e. the relation between the energy and momentum of the exchanged or propagating virtual photon does not give the rest mass: $E^2 - p^2 \neq m^2$. The quanta of the force of gravitation are called gravitons for which the coupling constant or "charge" is the (gravitational) mass of the particle. Although gravity is the main force we experience in our daily lives, the quantum theory of gravity remains to be worked out at present. Since gravity is irrelevant to elementary particle physics, apart from the fact that the (inertial) mass is a fundamental property of all particles, it will be largely ignored here.[1]

The changing concept of the strong and weak interactions, and what constitutes an "elementary particle," are intertwined with the principal issues of this book and will be discussed in due course.

1.3 A new paradigm for the structure of matter

Before 1968, matter was thought to be composed of atoms with a positively charged nucleus of small diameter ($\lesssim 10 \times 10^{-15}$ m) at the center surrounded by a cloud of negatively charged electrons at a much larger radius ($\sim 100 \times 10^{-12}$ m). This is called the Rutherford–Bohr model of matter because Ernest Rutherford [9]

[1] The equivalence of inertial and gravitational masses is known as the weak equivalence principle and was first demonstrated by Eötvös in an experiment using a torsion balance in 1889. This equivalence is responsible for the universal free fall velocity in vacuum independent of mass, first demonstrated by Galileo. So far as we know, this has not been demonstrated for quarks.

discovered the nucleus in 1911, and Neils Bohr, in 1913, discovered a quantum based model of the atomic electrons which explained the empirical Rydberg formula for the spectral lines of hydrogen [10–12]. In 1932, Chadwick discovered the neutron [13], and it became generally accepted [14, 15] that the nucleus was composed of a collection of protons and neutrons held together by a nuclear or "strong" force which counteracted the electrical repulsion of the positively charged protons. Also, in the period 1930–1933, Pauli proposed the existence of a massless spin 1/2 particle [16, 17] to solve the problem of apparent energy non-conservation in the radioactive β decay of a nucleus, $A \to B + e^-$, which showed a continuous energy spectrum of e^-, in contrast to α decay of a nucleus, $C \to D + \alpha$, where the alpha particle has a unique energy, $E_\alpha = E_C - E_D$. In 1934, Fermi [18, 19] then completed the picture of the weak interaction as the force responsible for the β radioactive decay of nuclei via the point-like interaction $n \to p^+ + e^- + \nu$, with a universal coupling constant G_F. He also named Pauli's particle the neutrino.

In the 1950s, systematic measurements of the radii and internal charge distribution, or "form factor," of nuclei by Robert Hofstadter led to his discovery that the proton itself had a finite radius [20]. Then, in the early 1970s, it became clear that the nucleon was not an elementary particle but was composed of a substructure of three valence quarks confined into a bound state by a strong interaction, Quantum ChromoDynamics (QCD), which is mediated by the exchange of color-charged vector gluons [21]. In sharp distinction to the behavior of the uncharged quanta of Quantum Electrodynamics (QED), the color-charged gluons of QCD interact with each other. This leads to the property of asymptotic freedom [22,23], the reduction of the effective coupling constant at short distances, and is believed to provide the confinement property at long distances where the quarks and gluons behave as if attached to each other by a color string. It is worth reviewing some developments leading up to and immediately following the discovery of QCD.

1.4 The particle zoo

Before World War II, when the few existing accelerators had too low an energy for the production of new particles in nucleon–nucleon collisions, high energy physics was largely an occupation of cosmic ray physicists, who made some important and fundamental discoveries including:

- the positron, the anti-particle of the electron;
- the muon, a particle with the same quantum numbers and weak and electromagnetic coupling constants as the electron, with the same property of no strong interaction but with a rest mass 207 times larger;
- the π-meson, originally thought to be the quantum of the strong interaction [24];

the "strange" particles which are produced in pairs at a rate corresponding to the strong interaction, but decay "slowly" at a rate corresponding to the weak interaction and appear as Vs in photographs [25].

In the early 1960s, with the construction of proton accelerators with energies well above the threshold for antiproton production, a veritable "zoo" of new particles and resonances was discovered [26]. Gell-Mann [27] and Ne'eman [28] noticed that particles sharing the same quantum numbers (spin, parity) follow the symmetry of the mathematical group SU(3) which is based on three elementary generators, up, down, strange, or u, d, s, with spin 1/2 and fractional electrical charge [29,30], which Gell-Mann called quarks. Mesons are described as states made of a quark–antiquark ($q\bar{q}$) pair and baryons as states of three quarks (qqq). This led to the prediction of a new baryon, the Ω^- (sss) with strangeness -3, which was observed shortly thereafter [31]. However, the Ω^- had a problem: three identical s quarks in the same state, apparently violating the Pauli exclusion principle. To avoid this problem, it was proposed [32] that quarks come in three "colors," i.e. distinguishing characteristics which would allow three otherwise identical quarks to occupy the same state (formally, para-Fermi statistics of rank 3). A major breakthrough was the realization that the fundamental SU(3) symmetry of nature was not the original three quarks uds (now called "flavor"), but the three colors, and that color-charged gluons are the quanta of the "asymptotically-free" strong interaction which binds hadrons [21]. The fourth "charm" or c quark, proposed to explain the absence of certain channels in weak decays of strange particles [33], thus had no problem fitting into this scheme – the quark symmetry became groups of doublets, ud, cs.

Elegant as these theories were, there are many other beautiful theories from this period that were not confirmed by experiment. It is the experimental results which sometimes lead and sometimes follow the theory that give the true picture of nature when in agreement. We would not go as far as Charles Peyrou in describing the cosmic ray discoveries who said: "Two of the discoveries (in cosmic ray physics) were predicted by theory: the positron and the π meson but in no case was the hand of the experimenter guided by the the theorist" [25]. From the point of view of the experimentalist, those were the good old days: "when the experiments were made of wood and the physicists were made of steel" [34]. Times are different now, as illustrated by the motivation for the next stage of discovery which came from a different direction and with a strong theory–experiment interplay with lots of discoveries on both sides.

1.5 The first high p_T physics, the search for the W boson

In the year 1960, Lee and Yang proposed the intermediate bosons $W^{\pm}$ as the quanta that transmit the weak interaction [35,36], and experiments were proposed to detect them with high energy neutrinos [37, 38]. Neutrino beams at the new BNL-AGS and CERN-PS accelerators provided the first opportunity to study weak interactions at high energy, whereas previously weak interactions had only been studied via radioactive decay. The first round of high energy neutrino experiments led to the discovery of a second neutrino [39] that coupled only to muons, in addition to the original (now electron) neutrino from β decay which coupled to electrons. This led to the concept of families of leptons with conserved lepton number (and later by analogy to generations or "flavors" of quarks). The $W^{\pm}$ was not observed in these experiments and only modest limits on the mass of the W (>2 GeV) were obtained due to the relatively low energies of the neutrino beams. However, it was soon realized that the intermediate bosons that mediate the weak interaction might be produced more favorably in nucleon–nucleon collisions [40–42] than in neutrino interactions. The signature of the heavy $W^{\pm}$ would be given by the two-body semi-leptonic decay:

$$W^{+} \to e^{+} + \nu_e \qquad \text{or} \qquad W^{+} \to \mu^{+} + \nu_{\mu}, \tag{1.1}$$

which would create a flux of seemingly direct leptons at large transverse momenta. However, the transverse momentum spectrum of single leptons from hadron collisions would be composed of the unavoidable, but smoothly falling, background from the decays of short lived hadrons, which decreased exponentially with increasing p_T according to the Cocconi formula, e^{-6p_T} [43, 44], upon which would be superimposed a peak at lepton transverse momentum

$$p_T = \frac{1}{2} M_W \tag{1.2}$$

for the assumed isotropic decay, where M_W is the mass of the intermediate boson. This beautiful idea, elegant in its simplicity and qualitativeness, soon became the stimulus of a large body of work both experimental and theoretical.

However, an objection was raised to the simple idea, when it was realized [45] that the interpretation of such experiments, particularly those with null results [46–48], would be impossible unless the form factor for the production of the intermediate boson were known. This form factor could be deduced [49] from the measurement of lepton pair production in hadron collisions; but the existence of such lepton pairs would create additional background in the single lepton spectrum, thus making the detection of a peak more difficult, if not impossible.

This new idea established the fundamental relationship between single lepton and lepton pair experiments and indicated the importance of doing both types of measurements. Nevertheless, the cross sections for producing the $W^{\pm}$ in hadron collisions remained a priori unknown until the complementary results of the measurement of di-lepton production in proton–nucleus collisions at BNL [50]

$$p + A \to \mu^+ + \mu^- + \text{anything} \tag{1.3}$$

and deeply inelastic electron–proton scattering (DIS) at SLAC [51–54]

$$e + p \to e + \text{anything} \tag{1.4}$$

paved the way for a revolution in the concept of the structure of the proton as a composite formed of quarks and gluons and the strong interactions as mediated by color-charged gluons exchanged by color-charged quarks and gluons.

There were four key experimental observations that made the composite theory of hadrons believable:

(1) the discovery of point-like constituents ("partons") inside the proton, in deeply inelastic (large energy loss, ν, large four-momentum transfer, Q) electron–proton (ep) scattering (DIS) at the Stanford Linear Accelerator Center (SLAC) [51–54];
(2) the complementary discovery of di-lepton production in $p + A$ collisions [50] which showed that the partons of DIS could annihilate into a $\mu^+\mu^-$ pair with electromagnetic strentgh [54];
(3) the observation of enhanced particle production at large transverse momenta (p_T) in p–p collisions at the CERN-Intersecting Storage Rings (ISR) [3, 55–57] and Fermilab [58,59] in experiments searching for single $e^\pm$ from the $W^\pm$, which proved that the partons of DIS interacted much more strongly with each other than the electromagnetic scattering observed at SLAC;
(4) the observation of the J/Ψ, a narrow bound state of $c\bar{c}$, in both p + Be collisions at the BNL-AGS [60], and in e^+e^- annihilations at SLAC [61], shortly followed by observation of the Ψ', a similar state with higher mass [62] which corresponded to $c\bar{c}$ bound states in a simple Couloumb-like potential with a string-like linear confining potential [63–66].

These discoveries turned Gell-Mann and Zweig's quarks from mere mathematical concepts to the fundamental constituents of matter, the components of the nucleon [67–71] and led to an entirely new vision of the strong interaction.

1.6 From Bjorken scaling to QCD to the QGP

The fundamental idea to emerge from DIS, which was the basis of much of the subsequent theoretical developments leading to QCD, was the concept of Bjorken scaling [72] which indicated that protons consist of point-like objects (partons). The structure function $F_2(Q^2, \nu)$ which describes the inelastic ep scattering cross section was predicted to "scale" [72], i.e. to be a function only of the ratio of the variables, Q^2/ν, which was observed [2, 51, 53], where Q^2 is the four-momentum transfer squared and ν is the energy transfer from the electron to the target. The deeply inelastic scattering of an electron from a proton is simply incoherent quasi-elastic scattering of the electron, which exhibits the standard elastic scattering recoil energy loss, $\nu = Q^2/2(Mx)$, from point-like partons of effective mass Mx, where M is the rest mass of the proton. Thus the Bjorken "x" is the fraction of the nucleon momentum (or mass) carried by the parton. Similar ideas for the scaling of longitudinal momentum distributions in p–p collisions were also given [73, 74]. However, these ideas related to the "soft" (low p_T) particle production rather than the large p_T or "hard scattering" processes described by Bjorken [75, 76].

Bjorken scaling was the basis of QCD [21], the MIT Bag model [77] and also led to the conclusion [78] that "superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons," because the hadrons overlap and their individuality is confused. Collins and Perry [78] called this state "quark soup" but used the equation of state of a gas of free massless quarks from which the interacting gluons acquire an effective mass, which provides long-range screening. They anticipated superfluidity and superconductivity in nuclear matter at high densities and low temperatures. They also pointed out that for the theory of strong interactions (QCD), "high density matter is the second situation where one expects to be able to make reliable calculations – the first is Bjorken scaling." In the Bjorken scaling region, the theory is asymptotically free at large momentum transfers while in high-density nuclear matter long-range interactions are screened by many-body effects, so they can be ignored and short distance behavior can be calculated with the asymptotically free QCD and relativistic many-body theory. Shuryak [79] codified and elaborated on these ideas and provided the name "QCD plasma," or "Quark–Gluon Plasma" (QGP) for "this phase of matter," a plasma being an ionized gas.

1.7 Relativistic heavy ion collisions and the QGP

It was soon realized that the collisions of relativistic heavy ions could provide the means of obtaining superdense nuclear matter in the laboratory [80–83]. The kinetic energy of the incident projectiles would be dissipated in the large volume of nuclear matter involved in the reaction. The system is expected to come to equilibrium, thus heating and compressing the nuclear matter so that it undergoes a phase transition from a state of nucleons containing bound quarks and gluons to a state of deconfined quarks and gluons, the quark–gluon plasma, in chemical and thermal equilibrium, covering the entire volume of the colliding nuclei or a volume that corresponds to many units of the characteristic length scale. In the terminology of high energy physics, this is called a “soft” process, related to the QCD confinement scale [84]

$$\Lambda_{QCD}^{-1} \simeq (0.2\ \mathrm{GeV})^{-1} \simeq 1\ \mathrm{fm}. \tag{1.5}$$

One of the nice features of the search for the QGP is that it requires the integrated use of many disciplines in physics: high energy particle physics, nuclear physics, relativistic mechanics, quantum statistical mechanics, and recently, string theory [85, 86]. From the point of view of an experimentalist there are two major questions in this field. The first is how to relate the thermodynamic properties (temperature, energy density, entropy, viscosity . . .) of the QGP or hot nuclear matter to properties that can be measured in the laboratory. The second question is how the QGP can be detected.

One of the major challenges in this field is to find signatures that are unique to the QGP so that manifestations of this new state of matter can be distinguished from the “ordinary physics” of colliding nuclei (without the production of a QGP). Another more general challenge is to find effects which are specific to $A+A$ collisions, such as collective or coherent phenomena, in distinction to cases for which $A+A$ collisions can be considered as merely an incoherent superposition of nucleon–nucleon collisions [87–89]. Hence it is important to understand the underlying high energy physics of nucleon–nucleon collisions in order to interpret clearly the results of $A+A$ collisions. This makes the field of RHI physics one of the only places where the older results of high energy physics in p–p collisions can be applied, while the elementary particle physics moves on to higher energy frontiers to gather new knowledge, for example the answers to the following questions.

(i) Are there undiscovered principles of nature: new symmetries, new physical laws?
(ii) Does the Higgs boson exist as a real particle? Does the Higgs mechanism give mass to the quarks and leptons as well as to the fundamental bosons?
(iii) Do quarks and leptons have a finite size? Is there a fundamental length?
(iv) How can we solve the mystery of dark energy?
(v) Are there extra dimensions of space?
(vi) Do all the forces become one?
(vii) Why are there so many kinds of particles?
(viii) What is dark matter? How can we make it in the laboratory?
(ix) What are neutrinos telling us?
(x) How did the universe come to be?
(xi) What happened to the antimatter?

1.8 High energy physics and techniques in the RHI physicist's toolkit

One must not forget that in addition to QCD [90], which is the underlying theory of the QGP, one of the important legacies of high energy physics to relativistic heavy ion physics is the catalog of elementary particles and quanta. It is important to realize, as discussed above, that the definition of the "elementary" particles and fundamental interactions is time dependent according to our state of knowledge.

Before 1930, the table of elementary particle was very simple:

$$\begin{array}{cc} \left(p^{+}\right) & \left(e^{-}\right) \\ \text{proton} & \text{electron.} \end{array}$$

After 1934, a table of the elementary particles could be represented as:

$$\begin{array}{cc} \begin{pmatrix} p^{+} \\ n^{0} \end{pmatrix} & \begin{pmatrix} e^{-} \\ \nu^{0} \end{pmatrix} \\ \text{nucleon} & \text{lepton.} \end{array}$$

There are two sets of two particles: nucleons (proton and neutron) and leptons (electron, neutrino), with electric charges indicated. One set has strong interactions, the other does not. In each set one particle has electric charge, while the other is neutral. All particles participate in the weak interaction via the decay $n \to p+e+\nu$. The grouping in doublets is significant because the strong interaction was found to be "charge independent," the same between n–p, p–p, n–n, so that the proton and neutron were taken to be two different states of the same particle, the nucleon [91], in analogy to the up and down states of spin 1/2 particles. This was called "isotopic spin" by Wigner [92]. The corresponding effect for the leptons is called "weak isospin" since it only involves the weak interaction.

The most up to date table of elementary particles, circa 2009, is both quantitatively and qualitatively different, but retains the doublet structure (Figure 1.2 [93, 94]). There are now six "flavors" of leptons and six "flavors" of quarks grouped in doublets forming three "generations." There is another set of anti-particles for each quark and lepton, not shown. Each of the quarks and antiquarks comes in three colors (red, green, blue) which are the "charges" of the strong interaction, mediated by the gluon (g) which comes in eight color charges (e.g. blue–anti-red, . . .). The leptons do not carry color and hence do not participate in the strong interaction. The four other force carriers are γ, Z^0, W^+, W^- of the now unified weak and electromagnetic (electroweak) interaction [95–97] in which the photon (γ) still couples only to electric charge and retains its zero rest mass while the $W^{\pm}$ and Z^0 masses of $\sim$100 GeV correspond to the short range ($\sim 2 \times 10^{-18}$ m) of the weak interaction. All leptons and quarks participate in the weak interaction with