Chapter 1
Particles and Forces

Abstract Radiation consists, ultimately, of subatomic matter and non-matter particles (e.g. photons) and nuclei. The mechanisms by which radiation impacts the surrounding world is determined by the laws that govern subatomic particle interactions. This chapter presents the elementary and composite particles discovered so far and introduces the forces by which these particles interact. The emphasis is placed on an overview of the current knowledge in this field, rather than an historical or theoretical account of the topic.

1.1 Units of Energy and Mass

The unit traditionally in use for the measurement of particle and radiation energy is the *electronvolt* (eV). It is defined as the kinetic energy gained by an electron after accelerating through a potential difference of 1 volt. Amounts of energy expressed in electronvolts are often found with prefixes kilo- (keV), mega- (MeV), giga- (GeV), tera- (TeV):

$$1\ \text{keV} = 10^3\ \text{eV}; \tag{1.1}$$
$$1\ \text{MeV} = 10^6\ \text{eV}; \tag{1.2}$$
$$1\ \text{GeV} = 10^9\ \text{eV}; \tag{1.3}$$
$$1\ \text{TeV} = 10^{12}\ \text{eV}. \tag{1.4}$$

In SI units,[1] the electronvolt corresponds to an extremely small amount of energy, tribute of the fact that the unit is practical to describe energies proper of the atomic and subatomic world. In fact, by its definition the electronvolt corresponds to 1 volt (1 joule per coulomb) multiplied by the electron charge ($1.602\,176\,565(35) \times 10^{-19}$ C) and is therefore:

$$1\ \text{eV} = 1.602\,176\,565(35) \times 10^{-19}\ \text{J}. \tag{1.5}$$

[1] SI is the International System of Units, in which the energy is measured in joule (J).

L. Cerrito, *Radiation and Detectors*, Graduate Texts in Physics,
DOI 10.1007/978-3-319-53181-6_1

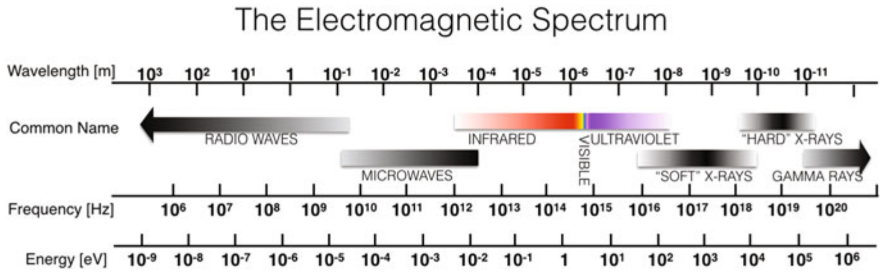


Fig. 1.1 The electromagnetic spectrum with the name of common types of radiation

Two fundamental constants are important in treating elementary particles. The Planck constant (h) relates in quantum mechanics the energy of a photon with its frequency by the relationship:

$$E = h\nu = hc/\lambda \text{ (or also } E = \hbar\omega), \tag{1.6}$$

where ν, ω and λ are the frequency, angular frequency, and wavelength of the photon, respectively, and c is the speed of light. Figure 1.1 shows the electromagnetic spectrum indicating the wavelength, frequency and energy (in eV) of common types of electromagnetic radiation. The human eye is sensitive to electromagnetic radiation with wavelengths between approximately 390 and 700 nm.

The symbol $\hbar$ is the *reduced* Planck constant, given by $\hbar \equiv h/2\pi$. The Planck constant has the dimension of action (or angular momentum), that is energy multiplied by time or momentum multiplied by distance and is an extremely small number when expressed in units of both joule or electronvolt:

$$h = 6.626\,069\,57(29) \times 10^{-34}\,\mathrm{J\,s} = 4.135\,667\,516(91) \times 10^{-15}\,\mathrm{eV\,s} \tag{1.7}$$

and therefore $\hbar \simeq 1 \times 10^{-34}\mathrm{J\,s} = 6.6 \times 10^{-16}\,\mathrm{eV\,s}$. Another fundamental constant is the speed of light, which in vacuum is:

$$c = 299\,792\,458\ \mathrm{m\,s^{-1}} \simeq 3 \times 10^{8}\,\mathrm{m\,s^{-1}}. \tag{1.8}$$

The constants c and h are so common in equations of particle dynamics that it has become customary to define conversion factors such that the speed of light and the reduced Plank constant are equal to 1 ($c = \hbar = 1$, *natural units*). To do this, the length is defined as the distance travelled by light in vacuum in one unit of time, so $c = 1$ and length and time are measured in the same units.

Furthermore, since in relativistic kinematics (see Chap. 4) the relativistic mass of a particle is related to its energy by:

$$E = m\,c^2, \tag{1.9}$$

this implies that masses are measured in units of eV/c^2. Similarly, the *momentum* $\mathbf{p}$ of a particle is related to its relativistic mass and velocity $\mathbf{v}$ by:

$$\mathbf{p} = m\,\mathbf{v}, \tag{1.10}$$

and therefore momentum is measured in units of eV/c. In natural units because $c = 1$ then masses, momenta, and energies (see (1.9) and (1.10)) are all expressed in the same units (eV). With $\hbar = 1$ and $c = 1$, the (1.6) shows that inverse lengths (L) and inverse times (T) are also measured in units of energies (E), since:

$$\left[\frac{1}{L}\right] = \left[\frac{E}{hc}\right] \quad \text{and} \quad \left[\frac{1}{T}\right] = \left[\frac{E}{h}\right] \tag{1.11}$$

Natural units are used throughout this textbook, however numerical results can be restored with the use of the numerical values of $\hbar$, c, and of the conversion factor:

$$\hbar c = 1.97 \times 10^{-16}\ \mathrm{GeV\,m}. \tag{1.12}$$

1.2 Elementary Particles and Antiparticles

The quest to understand and categorise the constituents of everyday matter, including the building blocks of our body, the objects surrounding us, the planets and stars in the Universe, has driven the field of experimental physics towards the examination of progressively smaller distances. For instance, structures called molecules are visible in substances at a scale of 10^{-8} to 10^{-10} m, and individual atoms appear on a scale of 10^{-10} to 10^{-11} m (the distance 10^{-10} m is called one ångström, 1 Å). Atoms are formed, in a simplified picture, by a nucleus of protons and neutrons combined with a shell of electrons (e). The nucleus appears to have a size of 10^{-14}–10^{-15} m (the distance 10^{-15} m is called one fermi, 1 fm) and its constituents, the proton and the neutron (see Fig. 1.2) are detectable at a distance of 10^{-15} m. Notice that there is a difference of about three to four orders of magnitude between the size of the atom and the size of its nucleus, so that the majority of the space within an atom is actually empty space. The energy corresponding to the characteristic size of an atom can be calculated from (1.11):

$$\mathscr{E}_{atom} = \frac{\hbar c}{1\text{Å}} = 1.97 \times 10^{-16}\ \mathrm{GeV\,m} \times 10^{10}\ \mathrm{m}^{-1} \approx \mathrm{keV} \tag{1.13}$$

and for the size of the nucleus, 10^{-14} m, that energy is $\mathscr{E}_{nucleus} \approx 10$ MeV.

When probing distances smaller than 10^{-18} m, the proton and the neutron reveal a substructure of quarks. Two quark types, called the *up* quark (u) and the *down* quark (d), are the dominant constituents of the proton and neutron. The energy corresponding to a scale of 10^{-18} m (the dimensional scale of quarks) is $\mathscr{E}_{quark} \approx$ 100 GeV.

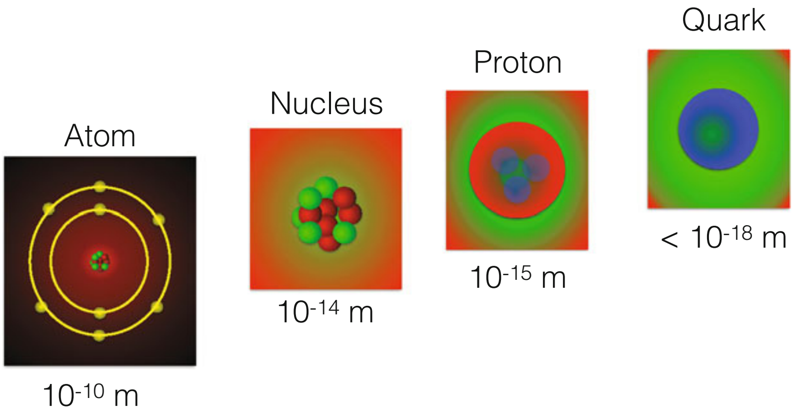


Fig. 1.2 The building blocks of the Universe and all everyday objects seem to consist of only quarks and electrons. On a scale of 10^{-10} m they combine to form atoms

Modern particle accelerators, such as the CERN Large Hadron Collider, are capable of probing distances of the order of up to about 10^{-21} m and at this distance there is no visible substructure to either the electron or the quarks. Quarks and electrons are therefore, as of today, the fundamental building blocks (meaning the matter particles) of the atoms.

Besides the electron and the up and down quarks mentioned above, there are additional fundamental particles that have been observed. They appear to be produced readily as a result of particle collisions as well as in particle decays. The elementary particles discovered so far and forming the matter of the Universe are summarised in Table 1.1.

The fundamental particles are classed into three families of two leptons and two quarks, and each higher-ranked family contains particles identical to the lower family except for a larger mass. The first family of leptons consists of the electron and the electron neutrino. The *muon* (μ) and the *tau* (τ) leptons share the same charge and spin of the electron but are heavier; the heavier mass changes the phenomenology of these particles, e.g. it influences their decays and lifetime compared to the electron which is stable. The muon has a mean lifetime of 2.2×10^{-6} s before decaying to an electron and two neutrinos (one of electron type and one of muon type), whereas the τ has much shorter mean lifetime of 2.9×10^{-13} s and decays primarily to hadrons (see Sect. 1.5). The different lifetime is explained by the large difference of mass between the μ and the τ.

Similarly to the leptons, the first family of quarks (the one containing the up and down quarks) is replicated in two additional families of unstable heavier quarks: *charm (c), strange (s), top (t)* and *bottom (b)*. They all have fractional electric charge of +2/3 or −1/3 in units of the electron charge. The top quark, in the third family,

Table 1.1 Elementary particles (fermions)

Particle	Family	Class	Symbol	Spin	Electric charge[a]	Mass[b]	Mean lifetime[c] (s)
Electron neutrino	I	Lepton	ν_e	1/2	0	<2 eV	Stable
Electron	I	Lepton	e^-	1/2	-1	0.5 MeV	Stable
Up	I	Quark	u	1/2	+2/3	2 MeV	Hadronise
Down	I	Quark	d	1/2	$-1/3$	5 MeV	Hadronise
Muon neutrino	II	Lepton	ν_μ	1/2	0	<0.19 MeV	Stable
Muon	II	Lepton	μ^-	1/2	-1	106 MeV	2.2×10^{-6}
Charm	II	Quark	c	1/2	+2/3	1.3 GeV	Hadronise
Strange	II	Quark	s	1/2	$-1/3$	100 MeV	Hadronise
Tau neutrino	III	Lepton	ν_τ	1/2	0	<18.2 MeV	Stable
Tau	III	Lepton	τ^-	1/2	-1	1.8 GeV	2.9×10^{-13}
Top	III	Quark	t	1/2	+2/3	173 GeV	5×10^{-25}
Bottom	III	Quark	b	1/2	$-1/3$	5 GeV	Hadronise

[a]Electric charge is expressed in units of the electron charge
[b]Mass values shown are only approximate and measurements can be found in [1]. Except for the top quark, the mass of the quarks are estimates based on the properties of quark bound states (see Sect. 1.5)
[c]Mean lifetime values are only approximate and measurements can be found in [1]. Quarks that form bound states of hadrons might decay as part of an hadronic state (see Sect. 1.5)

is the heaviest fundamental particle ever discovered and its mass[2] of 173 GeV is similar to the mass of the entire nucleus in an atom of gold. As a reference, the mass of the proton is only about 1 GeV (approximately 938 MeV). The leptons and quarks have spin 1/2,[3] and in quantum mechanics particles with spin 1/2 obey Fermi's spin-statistics rule, i.e. they cannot occupy simultaneously the same quantum state; they are called *fermions*. For each fermion there is a corresponding antiparticle of the same mass but opposite electric charge, and collectively antiparticles are referred to as *antimatter*.

Antimatter was introduced in 1928 by Dirac [2] as a theoretical consequence of combining quantum mechanics and special relativity, and it was discovered in 1932 [3] through the detection of a positively charged particle with the same mass as the electron. The antielectron (e^+) is more commonly called a positron and is routinely produced through the decay of heavier particles. For every fermion in Table 1.1 the corresponding antiparticle is indicated by placing a dash above the particle symbol, so that for example $\bar{\nu}_e$ indicates an antineutrino and $\bar{t}$ an antitop, except for the

[2]The mass of particles is expressed in units of energy when using *natural* units, a full explanation is given in Sect. 1.1.

[3]Spin is a form of angular momentum possessed by elementary particles.

charged leptons for which the antiparticle is indicated by the positive charge sign as: e^+, μ^+ and τ^+.

Particle decays are indicated by the notation:

$$initial\ particle \rightarrow final\ particles, \tag{1.14}$$

and the same particle might decay into a number of different modes, called decay channels, each with its own probability. Considering all the correct symbols for particles and antiparticles, the decay of a muon to an electron and two neutrinos is therefore written as:

$$\mu^- \rightarrow e^-\ \bar{\nu}_e\ \nu_\mu. \tag{1.15}$$

It is worth mentioning that there is so far no experimental evidence to confirm that the antineutrino is indeed a different particle than the neutrino. For the positron and the electron for instance, it is sufficient to detect two particles of the same mass but with opposite sign electric charge. For a neutral, nearly massless, and weakly interacting particle the proof is vastly more difficult.

1.3 Fundamental Forces and the Higgs Boson

The elementary particles introduced in Sect. 1.2 interact with each other via one or more fundamental forces. These are the four known fundamental forces of nature: electromagnetic, weak nuclear, strong nuclear, and gravitational. The gravitational force, whilst present, is negligible at the level of subatomic particles when compared to the other three forces, and is therefore neglected in all considerations of particle dynamics. The electromagnetic and the weak nuclear force are conceptually unified in a mathematical description called electroweak interactions. This includes the electric and magnetic forces seen in the macroscopic world, as well as the weak nuclear force which was first observed in neutron decays. All quarks and leptons are subject to the electroweak interactions. Neutrinos are electrically neutral and therefore interact only via the weak force. The strong nuclear force is only felt by quarks.

The relative strength of these forces depends significantly on the distance at which they are probed. At distances of 10^{-18} m, i.e. the quark scale, if the strong interaction is taken as reference (with a strength of 1), the electromagnetic and weak forces have a similar strength of 10^{-2} and the gravitational force is immensely weaker, with a strength of 10^{-43}. The weak force however becomes much more feeble at a marginally larger distance, at 10^{-17} m it becomes about 10,000 times weaker than at 10^{-18} m.

Similarly to the electric charge, the strong nuclear force has an associated *colour* charge. This charge has of course nothing to do with the colours of visible light, but the word is aptly used to label the three types of charges present: red, green and blue. Furthermore, each of them can have two states, referred to as antired, antigreen and antiblue.

Table 1.2 Elementary particles (bosons)

Particle	Symbol	Interaction	Spin	Electric charge	Mass[a] (GeV)	Width (GeV)	Dominant decay mode
Photon	γ	Electromagnetic	1	0	0	Stable	–
W boson	$W^{\pm}$	Weak	1	± 1	80	2.1	$q\bar{q}'$[b], $\ell\nu_{\ell}$[c]
Z boson	Z^0	Weak	1	0	91	2.5	$q\bar{q}$, $\ell^+\ell^-$, $\nu_{\ell}\bar{\nu}_{\ell}$
Gluon	g	Strong	1	0	0	Stable	–
Higgs	H^0	–	1	0	126	$\sim 4 \times 10^{-3}$[d]	$b\bar{b}$, $W^{\pm}W^{\mp *}$

[a] Values for the $W^{\pm}$, Z^0, H^0 bosons are only approximate and measurements can be found in [1]
[b] q indicates any quark except the top
[c] ℓ indicates each type of lepton, e, μ and τ
[d] Prediction based on the Standard Model

The quantum-mechanical relativistic theory of the electroweak and strong interactions between elementary particles is called the *Standard Model*.

The Standard Model describes the particle interactions through the exchange of spin 1 particle carriers of the electromagnetic, weak and strong force. The photon (γ) is the carrier of the electromagnetic force, while the weak force is carried by the $W^{\pm}$ and Z^0 bosons. Finally, the strong force is carried by eight gluons (g). Table 1.2 summarises the fundamental forces and their particle carriers. The Z and W bosons are readily produced in high-energy particle collisions. The W boson is also produced in the decay of the top quark:

$$t \to W^+ b, \tag{1.16}$$

and the W itself then proceeds to decay into lighter particles, either to one lepton (e, μ or τ) with the corresponding neutrino, or to a pair of quark and anti-quark (all types except for the top quark, whose mass is too large).

The picture of the building blocks of the Universe is completed by an additional particle: the *Higgs* boson (H^0) [5–7]. The Higgs boson was discovered in 2012 by the ATLAS and CMS experiments [8, 9] at CERN's the Large Hadron Collider. The new particle was seen to have a mass of 126 GeV, and is key to explaining how leptons, quarks and the electroweak bosons acquire their own mass. In the Standard Model, the Higgs boson is the manifestation of the Higgs field and the quarks and leptons acquire their mass through their interaction with such a field. Different masses of leptons and quarks are explained by the different strengths of their coupling with the Higgs field.

Once produced, the Higgs boson decays to ordinary particles in a variety of decay channels. The event display in Fig. 1.3 shows the decay of an Higgs boson candidate as seen by the ATLAS detector to a pair of Z and finally to four electrons

$$H \to Z^0 Z^{0*} \to e^+ e^- e^+ e^-. \tag{1.17}$$

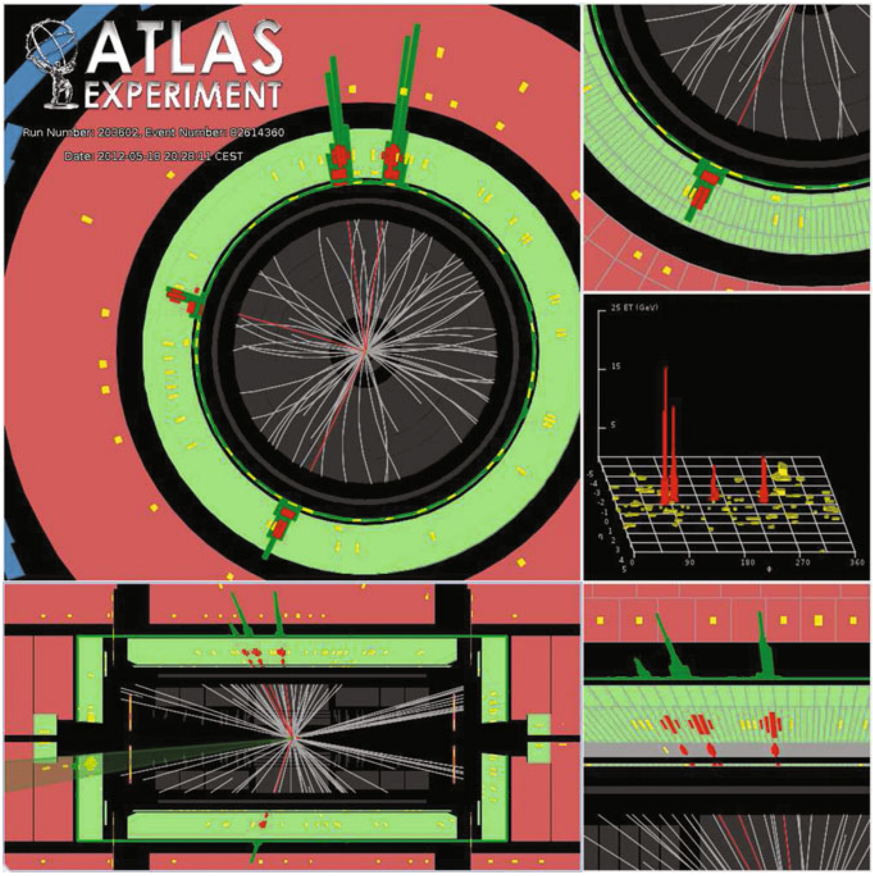


Fig. 1.3 The decay of a Higgs boson to four electrons as detected by the ATLAS experiment. The electrons are visible as *straight* lines in the inner tracking system and large *energy deposits* in the electromagnetic calorimeter. Reprinted with permission from [4]

The quadrant in the upper left shows a cross sectional view of the detector. The beams of protons enter the detector perpendicularly to the plane of the page and collide at the center of the concentric detector layers. Charged particles emerging from the collision are bent by a magnetic field and perform a helicoidal trajectory with radius inversely proportional to the component of their momentum perpendicular to the magnetic field. The four electrons are visible as almost-straight lines in the inner tracking system, and also as large *energy deposits* in the electromagnetic calorimeter. Although the dominant decay modes of the Higgs boson are $H^0 \to b\bar{b}$ and $H^0 \to W^{\pm}W^{\mp*}$, the Higgs boson is more easily distinguished from backgrounds in its rarer $H \to Z^0Z^{0*}$ and $H^0 \to \gamma\gamma$ final states.

1.4 Feynman Diagrams

The interaction between particles is described pictorially with the aid of *Feynman diagrams*. The sketch in Fig. 1.4 depicts the electromagnetic scattering between two electrons: $e^- + e^- \rightarrow e^- + e^-$ through the exchange of a single photon or a Z^0 boson. A line entering a diagram from the left-hand side is interpreted as a particle in the initial state, and one leaving a diagram on the right-hand side as one present in the final state. The electrons are represented by a solid line, while the photon, W and Z^0 by a wiggly line and the gluon by a curly line (see Fig. 1.5). By convention time flows from left to right, while the arrows point in the direction of motion for particles and in the opposite direction for antiparticles, so that charge conservation is implied at each vertex. In Fig. 1.4, both electrons can emit the exchanged photon.

The diagram in Fig. 1.6 represents one contribution to the so-called *Compton scattering*. The electron line at the center indicates both the initial electron emitting the final photon followed by absorption of the initial photon, or creation of an electron-positron pair by the initial photon followed by electron-positron annihilation of the initial electron.

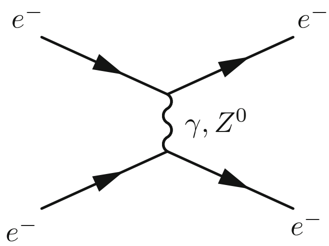


Fig. 1.4 Feynman diagram of an electron–electron scattering process characterised by the exchange of a photon or a Z^0 boson

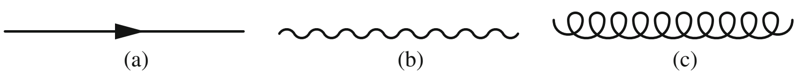
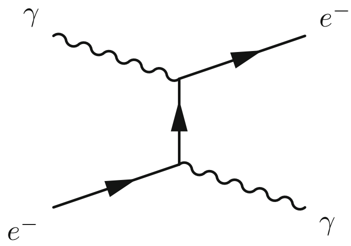


Fig. 1.5 Feynman diagrams of a fermion (**a**), photon or electroweak boson (**b**), and gluon (**c**)

Fig. 1.6 Feynman diagram of Compton scattering, $\gamma\ e \rightarrow \gamma\ e$



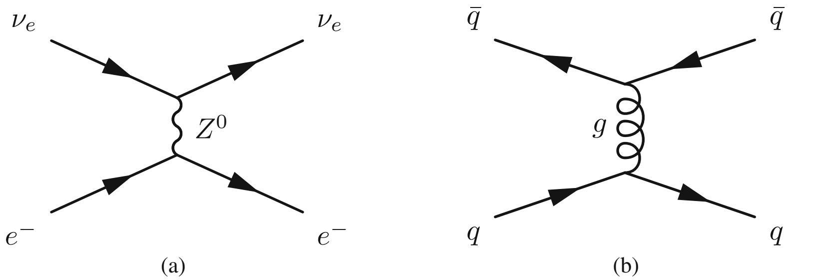
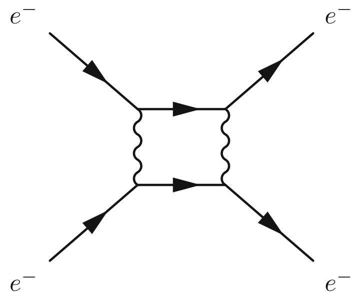


Fig. 1.7 Feynman diagrams showing the exchange of bosons in the interaction of leptons and quarks. **a** neutrino–electron scattering mediated by the exchange of a Z^0 boson. **b** quark–quark scattering mediated by a gluon exchange

Fig. 1.8 Contribution to electron–electron scattering from two-photon exchange



The illustrations in Fig. 1.7 show examples of the $\nu_e + e \rightarrow \nu_e + e$ scattering, mediated by a Z^0, and the gluon exchange process $q + \bar{q} \rightarrow q + \bar{q}$.

The interaction processes can also occur with the exchange of multiple particles, as shown by the two-photon exchange depicted in Fig. 1.8. However, since each vertex in the diagram represents a basic interaction, whose probability is dependent on the strength of the coupling between the particles involved, multiple vertices typically correspond to progressively smaller contributions to the same initial and final-state process. The number of vertices in a given Feynman diagram is called its *order* and the diagram with the least number of vertices for a given process is called a *Leading Order (LO)* diagram.

1.5 Hadrons

The quarks introduced in Sect. 1.2 form bound states (called *hadrons*) composed of either three quarks (qqq or $\bar{q}\bar{q}\bar{q}$, named *baryons*) or a pair of quark–antiquark ($q\bar{q}$, indicated as *mesons*). The quark bound states are the result of the strong nuclear force acting between the quarks. These configurations are the only ones that allow colourless bound states, either by pairing a red–green–blue combination of three quarks, or a colour–anticolour state of two quarks. All searches for free quarks have so far been unsuccessful, quarks have not been found free from hadrons, and our modeling of the strong nuclear force (a theory called *quantum chromodynamics*, QCD) incorporates the fact that they cannot do so. By pulling apart quarks, as it is for instance common in hadron colliders following the breakup of protons, the quarks will form bound states in a number that increases with the energy of the quark. Escaping quarks will therefore appear as a shower of hadrons moving in the direction of the original quark.

The event display in Fig. 1.9 shows a signature compatible with three high-energy quarks or gluons being emitted from the collision point of a proton–antiproton collision. The active detector is shown in cross sectional view, the colliding beams approaching from opposite directions perpendicular to the plane of the page, with the inner circle representing the tracking volume of the detector and the outer ring indicating the calorimeters. Charged particles appear as tracks in the inner detector, bent by a magnetic field, and coloured blocks in the calorimeters indicate an energy release. Because the quarks hadronise as they move away from the collision point at the center of the picture, they would appear as three jets of collimated particles.

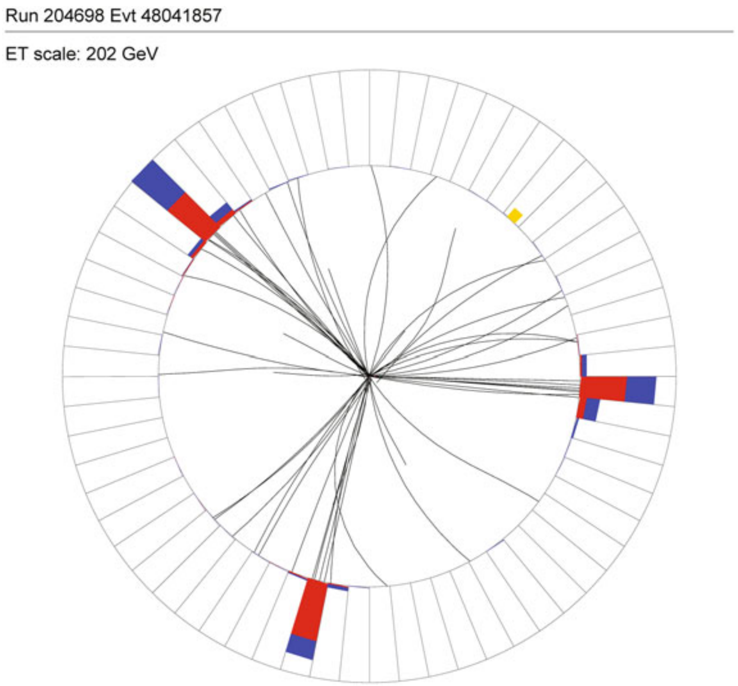


Fig. 1.9 Signature compatible with the hadronisation of three quarks or gluons emitted at high energy from the collision point (center of display) in this proton–antiproton collision, recorded by the D0 detector at the Tevatron collider. Printed with permission from [10]. Credit: Fermilab/DZero Collaboration

Table 1.3 The quark content of a selection of baryons (lowest levels)

Particle	Symbol	Quark content	Electric charge[a]	Mass[b] (GeV)	Mean lifetime[b] (s)	Dominant decay mode
Proton	p	uud	$+1$	1	Stable[c]	–
Neutron	n	udd	0	1	880[d]	$pe^-\bar{\nu}_e$
Lambda	Λ	uds	0	1.1	2×10^{-10}	$p\pi^-$
Xi	Ξ^0	uss	0	1.3	3×10^{-10}	$\Lambda\pi^0$
Omega	Ω^-	sss	-1	1.7	8×10^{-11}	ΛK^0
Lambda (c)	Λ_c^+	udc	$+1$	2.3	2×10^{-13}	p anything
Lambda (b)	Λ_b^0	udb	0	5.6	1×10^{-12}	Λ_c^+ anything

[a]Electric charge is expressed in units of the proton charge
[b]Mass and lifetime values shown are only approximate and measurements can be found in [1]
[c]Current measurements of the proton lifetime yield a limit of $> 10^{29}$ years
[d]This is the mean lifetime of a free neutron, i.e. not bound in a nucleus

Table 1.4 The quark content of a selection of mesons (lowest levels)

Particle	Symbol	Quark content	Electric charge[a]	Mass[b] (GeV)	Mean Lifetime[c] (s)	Dominant decay mode
Pion (±)	π^+, π^-	$u\bar{d}, d\bar{u}$	$+1, -1$	0.14	3×10^{-8}	$\mu\bar{\nu}_\mu, \mu^+\nu_\mu$
Pion (0)	π^0	$u\bar{u}, d\bar{d}$	0	0.14	8×10^{-17}	$\gamma\gamma$
Kaon (±)	K^+, K^-	$u\bar{s}, s\bar{u}$	$+1, -1$	0.49	1×10^{-8}	$\mu\bar{\nu}_\mu, \mu^+\nu_\mu, \pi^\pm\pi^0$
D (±)	D^+, D^-	$c\bar{d}, d\bar{c}$	$+1, -1$	1.9	1×10^{-12}	$K^0\bar{K}^0$ anything
B (0)	$B^0, \bar{B}^0$	$d\bar{b}, b\bar{d}$	0	5.3	1×10^{-12}	$\bar{D}^0X, D^-X$
$J/\Psi(1S)$	$J/\Psi(1S)$	$c\bar{c}$	0	3.1	93 keV	hadrons, e^+e^-, $\mu^+\mu^-$
$\Upsilon(1S)$	$\Upsilon(1S)$	$b\bar{b}$	0	9.5	54 keV	$\ell^+\ell^{-\,b}$

[a]Electric charge is expressed in units of the proton charge
[b]Mass and lifetime values shown are only approximate and measurements can be found in [1]
[c]ℓ indicates each type of lepton e, μ and τ

The event was recorded by the D0 detector at the US Fermilab's Tevatron Collider in 2005.

Conversely, the top is the only quark that does not form bound states, but only because it decays (almost always to a W boson and b quark) with a mean lifetime of $\sim 5 \times 10^{-25}$ s, which is about ten times faster than the time required to *hadronise*, i.e. to form the bound states of quarks.

The proton is composed primarily of uud quarks, and the neutron is a bound state of udd quarks. Historically, hadrons were discovered in increasing numbers and by 1955, the proton, the neutron and three pions (π^0, π^+ and π^-) were known, along with the antiproton and antineutron.

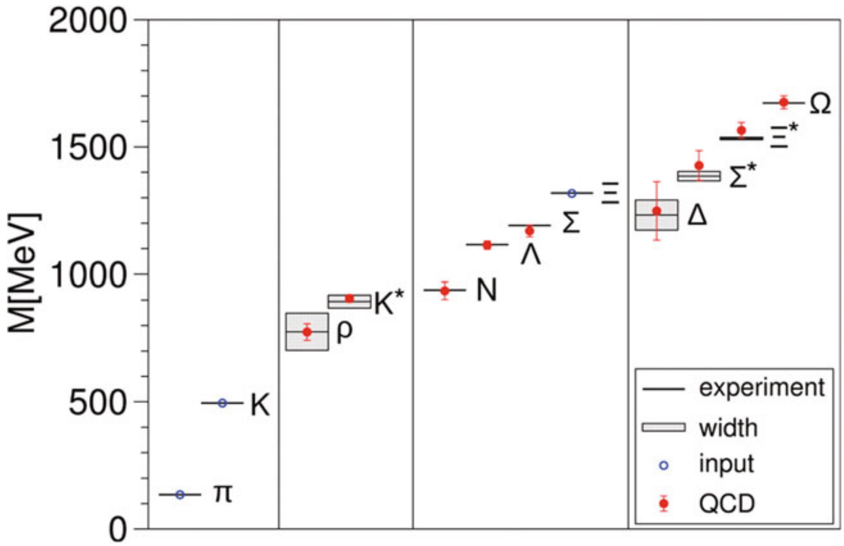


Fig. 1.10 The light hadron spectrum of QCD, from [14]. Reprinted with permission from AAAS

Quarks were subsequently postulated by Gell-Mann [11] and Zweig [12, 13] in 1964 to explain patterns of mass, charge and decay properties that characterised the observed hadrons. The quark content of several of the lowest level hadrons is summarised in Tables 1.3 and 1.4. All hadrons, except for the proton, are unstable and the neutron decays into a proton with a mean lifetime of 880 s [1].

The plot in Fig. 1.10 summarises the mass spectrum of light hadrons from the pion to the Ω. The lightest, pions and kaons, are the most commonly produced.

1.6 Lepton and Quark Numbers

Particle decays have been observed to occur under strict conservation rules. The conservation of energy and momentum are concepts of classical physics that are also valid in relativistic quantum mechanics. The conservation of the electric charge is also respected by the electroweak and strong interactions. Additional conserved quantities which are observed include for instance the *lepton number*, defined as:

$$L_\ell = N(\ell^-) + N(\nu_\ell) - N(\ell^+) - N(\bar{\nu}_\ell), \tag{1.18}$$

where ℓ is separately either e, μ or τ. Lepton number is conserved in decays mediated by electroweak interactions, so for instance the initial state in the muon decay process $\mu \to e\ \bar{\nu}_e\ \nu_\mu$ has muon number 1 and electron and tau numbers zero, and therefore the final state must also have muon number 1 (given by the ν_μ) and electron and tau numbers zero (the electron number is cancelled by the e and the $\bar{\nu}_e$).

The purely leptonic τ decay:

$$\tau^- \to \mu^- \; \bar{\nu}_\mu \; \nu_\tau \tag{1.19}$$

can also be readily seen to conserve the lepton numbers.

Examples of decays that would violate lepton number conservation include:

$$\mu^- \to e^- \; \gamma, \tag{1.20}$$

$$\tau^- \to e^- \; \mu^+ \; \mu^-, \tag{1.21}$$

$$\tau^- \to \mu^- \; \gamma, \tag{1.22}$$

and these are indeed not seen experimentally.

Hadronic states are also labelled by quark numbers: strangeness S, charm C, bottom B and top T. These quantities relate to the quark content of the hadron, so for instance a strange quark gives a contribution of $S = -1$ to an hadron which contains it. The hadron electric charge Q and the baryon number B, defined as:

$$\tilde{B} \equiv \frac{1}{3}[N(q) - N(\bar{q})] \tag{1.23}$$

complete the list of internal quantum numbers. These are important because strong and electromagnetic interactions conserve all quark numbers, since in these interactions quark are only produced in quark–antiquark pairs. However, weak interactions violate quark numbers; an example is given by the neutron decay

$$n \to \; p\, e^- \bar{\nu}_e, \tag{1.24}$$

which written in terms of quarks is:

$$(udd) \to \; (uud)\, e^- \bar{\nu}_e. \tag{1.25}$$

It is immediately evident in this transition that a d quark is replaced by a u quark in the final state. The corresponding Feynman diagram is shown in Fig. 1.11. The hadron is represented by the parallel lines of its constituent quarks.

The quark and baryon numbers play a fundamental role in understanding the decay of hadrons. The vast majority of hadrons decay via the strong interactions to lighter particles with the same quark and baryon numbers. When there are no lighter hadrons with the same internal quantum numbers the decay may proceed through the weak interaction, in which only the baryon number and electric charge are conserved, but the lifetime of these processes is much longer, by about 10 orders of magnitude.

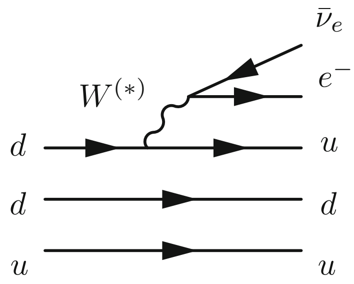


Fig. 1.11 Quark representation of the neutron decay

Glossary

Electronvolt (eV) Kinetic energy gained by an electron after accelerating through a potential difference of 1 volt

$$1\,\text{eV} = 1.602\,176\,565(35) \times 10^{-19}\,\text{J}.$$

SI International System of Units

Planck constant Fundamental constant that relates the energy of a photon with its frequency

$$h = E/\nu = 6.626\,069\,57(29) \times 10^{-34}\,\text{J s} = 4.135\,667\,516(91) \times 10^{-15}\,\text{eV s}$$

Ångström (Å) Distance corresponding to 10^{-10} m which is approximately the scale of an atom

Antimatter Collective name for the antiparticles

Baryons Composite particles which are bound states of three quarks or three antiquarks

Boson Particle with spin 1, such as the photon and the Higgs particle

Feynman diagram Pictorial mathematical representation of particle interactions

Fermi (f) Distance corresponding to 10^{-15} m which is approximately the scale of the atomic nucleus

Fundamental forces The four known fundamental forces of nature: electromagnetic, weak nuclear, strong nuclear, and gravitational

Hadrons Composite particles which are bound states of quarks

Higgs boson Particle manifestation of the Higgs field, whose existence is key to explaining how leptons, quarks and the electroweak bosons acquire their own mass

Lepton Elementary matter particle with spin 1/2, such as the electron, the muon and the neutrino

Mesons Composite particles which are bound states of one quark and one antiquark

Muon Elementary unstable particle belonging to the second family of the leptons. Its mass is 106 MeV and mean lifetime of 2.2 μs

Quark Elementary matter particle, present for instance in the protons and neutrons of an atomic nucleus

Standard Model Quantum-mechanical relativistic theory of the electroweak and strong interactions between elementary particles

Speed of light Fundamental constant which in vacuum corresponds to

$$c = 299\,792\,458\,\mathrm{m\,s^{-1}} \simeq 3 \times 10^{8}\,\mathrm{m\,s^{-1}}$$

Top quark The heaviest of the quarks, with a mass of 173 GeV

Ultraviolet (UV) Part of the electromagnetic spectrum corresponding to wavelengths between 100 nm and 400 nm

X-ray (soft) Electromagnetic radiation corresponding to wavelengths between 0.01 nm and 10 nm

X-ray (hard) Electromagnetic radiation corresponding to energies of the order 10–100 keV

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Radiation and Detectors
Introduction to the Physics of Radiation and Detection Devices
Cerrito, L.
2017, XIV, 210 p. 142 illus., 50 illus. in color., Hardcover
ISBN: 978-3-319-53179-3