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Stephan Narison
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Part I

General introduction

1

A short flash on particle physics

Since ancient times, we have been curious to know the origin and the nature of the universe.[1] Numerous ancient philosophers and scientists have tried to answer these fundamental questions. It is only at the present time of the twentieth millennium that we can provide a partial answer to these questions, as some significant progress has been accomplished in both particle physics and astrophysics, which are two areas of research in two apparently opposite scale directions (see Fig. 1.1).[2]

On the one hand, this progress is due to our ability to explore the heart of matter, with powerful accelerators (where the accelerated particle has a velocity near to the velocity of light), which reveal their infinitely small, deepest structure (see Fig. 1.2).

As an example, we show in Figs. 1.3 and 1.4, the large electron-positron (LEP) accelerator and the reaction inside the detector after the collision of the electron and the anti-electron (positron). Notice that at LEP, the energy of the electron is in the range of 90–180 GeV which is about $(5–10) \times 10^6$ times the energy of our home TV screen. On the other hand, powerful telescopes (see Fig. 1.5) explore the enormous structure of the universe, and may reach the time of its origin. At present, these apparently two opposite (in scale) areas of research are found to have a common feature as the conditions required for exploring the smallest structure of matters (quarks) reproduce the periods which followed the big-bang (see Fig. 1.6), from which one may understand the origin of the universe.[3]

In this book, we shall concentrate on one aspect of particle physics, called Quantum ChromoDynamics, which is a part of the so-called Standard Model (SM). We know that, at the beginning of the study of nuclear physics, it was observed that, in addition, to the well-known Newton gravitation and electromagnetism (Maxwell) forces, nature is governed by two other new forces, the weak interactions responsible of the β decay and the strong Yukawa force which binds the nucleons inside the nucleus (see Fig. 1.7).

In particle physics, only the last three forces play an important rôle as gravitation couples too weakly and cannot be directly detectable in particle physics experiments. At the particle

[1] This short review is based on the review talk in [4].
[2] Figures in this chapter come from [5].
[3] For a recent review on interfaces between these two fields, see e.g. [6].

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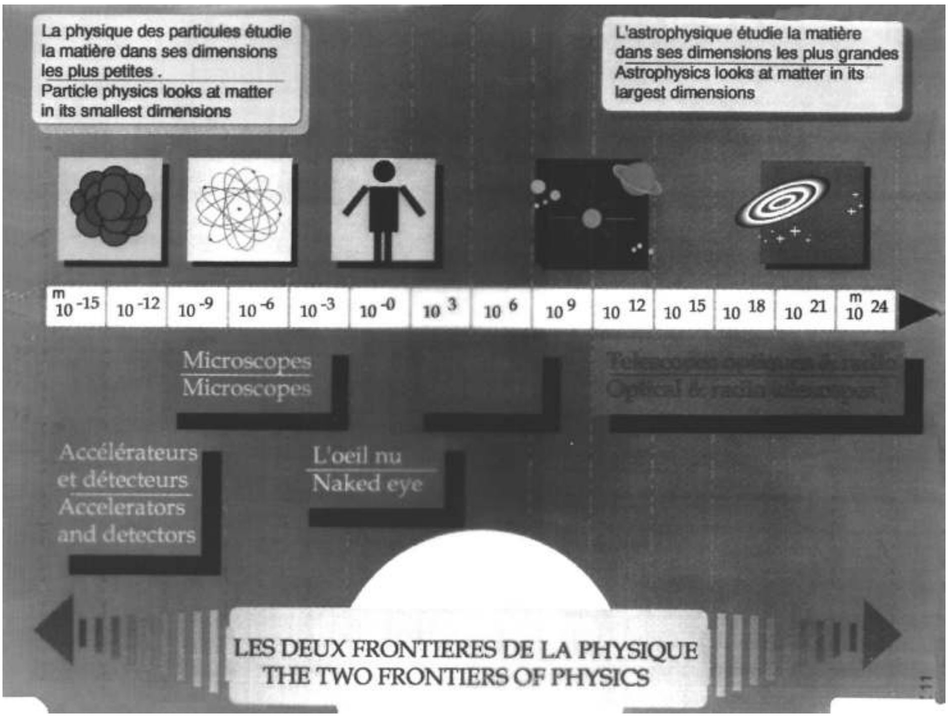


Fig. 1.1. A schematic view of the scales of the universe and related research branches. Our human body is taken as a reference scale (ref. CERN Z 11).

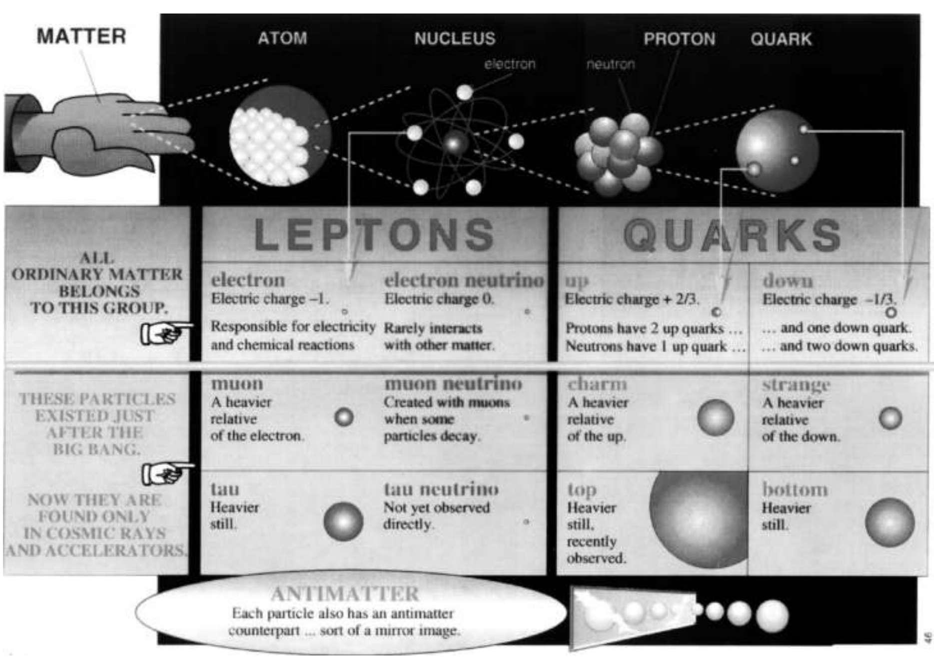


Fig. 1.2. The different structures of matter at different scales (ref. CERN DI-17-7-95).

Fig. 1.3. An aerial view of CERN-Geneva, showing the undeground LEP ring, 27 km in circumference, where also the LHC (large hadron collider) will run soon. In order to see the real size of the ring, one can see Geneva airport in the front part of the photo (ref. CERN X 973-1-87).

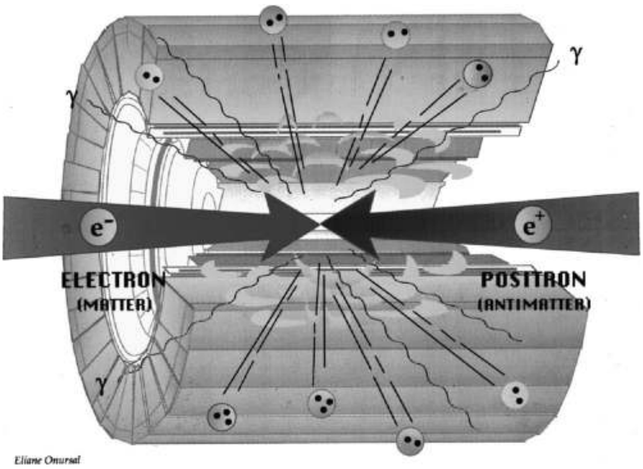


Fig. 1.4. A schematic view of the detector and particles produced after the collision (ref. cern DI-64-I-91).

Fig. 1.5. A photo of the Hubble telescope.

physics scale (below TeV), physics is well described by the SM $SU(3)_c \otimes SU(2)_L \otimes U(1)$, and the distinction between the three forces leads to the classification that: *Leptons* (e^-, ν_e) and (μ^-, ν_μ) pairs couple only to weak and electromagnetic $SU(2)_L \otimes U(1)$ forces (the neutral neutrino ν_l has only weak interactions), whereas *Hadrons* like the proton, neutron, pion and rho meson have mainly strong $SU(3)_c$ colour interactions.

However, one expects that at higher energy levels, of the order of 10^{15} GeV to the Planck scale, these three different forces which apparently are of different origins unify with gravitation, then leading to a much simpler description of nature and the realization of the old Einstein dream for the understanding of the universe laws. At present, the minimal version of supersymmetry based on the $SU(5)$ group (popularly called MSSM) is the best candidate for such a unified theory. Indeed, using the renormalization group evolution of the different couplings in the MSSM, one realizes that to second order in perturbation theory, these three couplings indeed cross with high precision at the unification scale of 10^{15} GeV as shown in Fig. 1.8. This result is encouraging although we still fail to find the correct

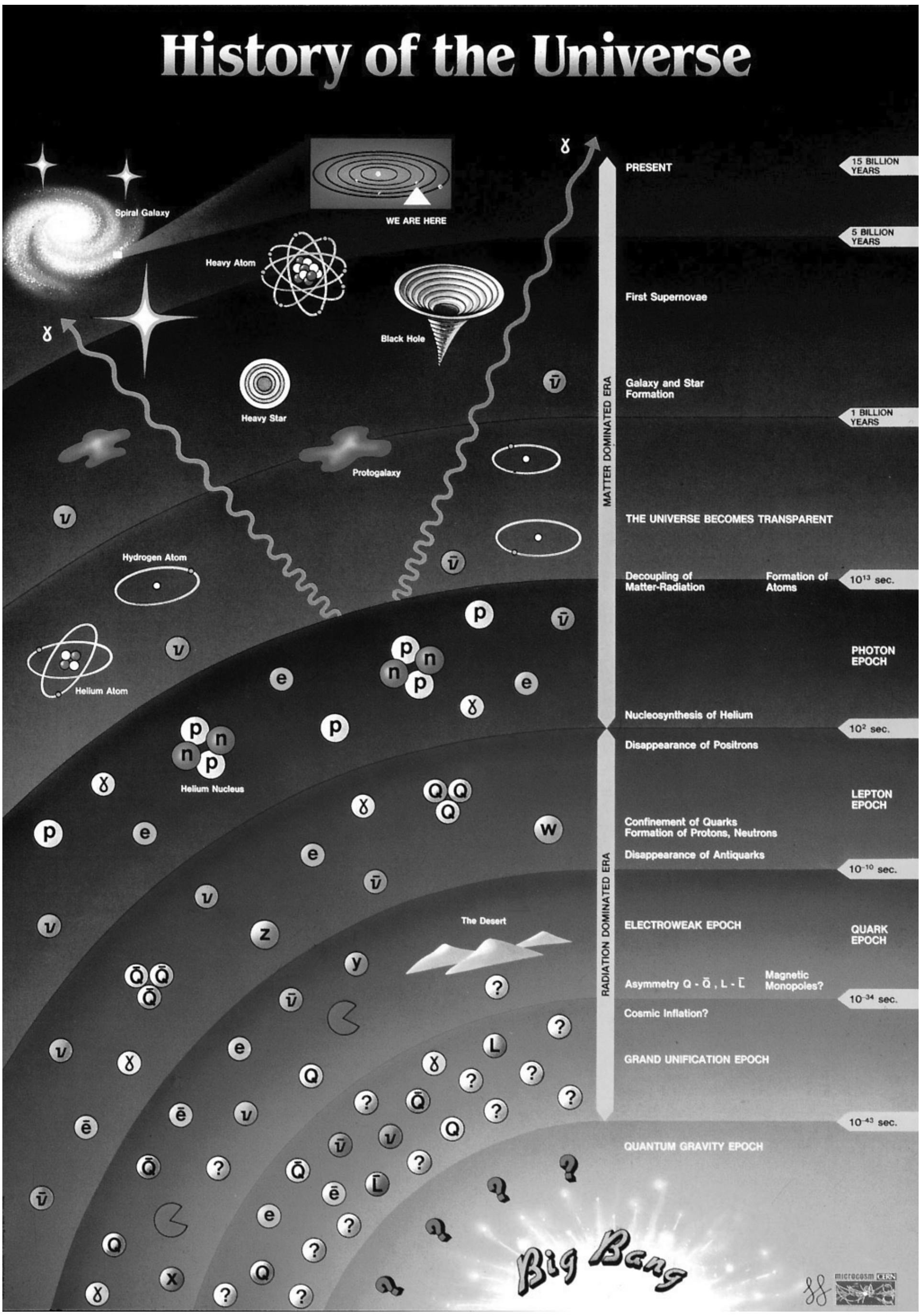
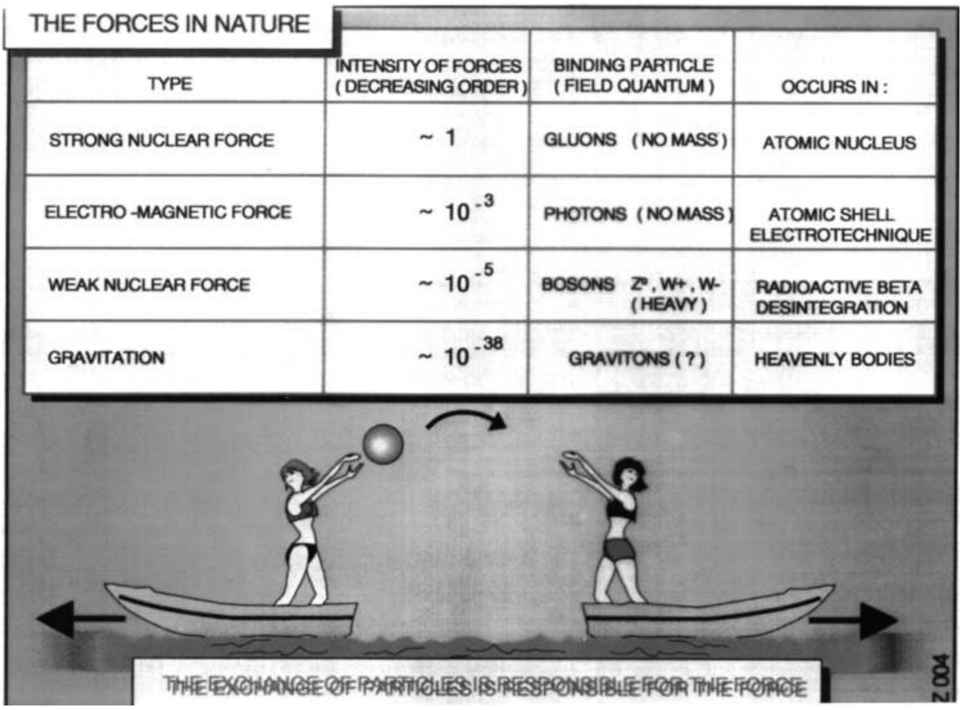


Fig. 1.6. A schematic view of the history of the universe from the big bang to the present day (ref. cern DI-2-8-91).



TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO-MAGNETIC FORCE	$\sim 10^{-3}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^0, W^+, W^- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES

Fig. 1.7. A schematic view of the different forces in nature, and their associated vehicles (gauge bosons). The reference force is a strong interaction of strength 10^{-12} cm (ref. cern Z 004).

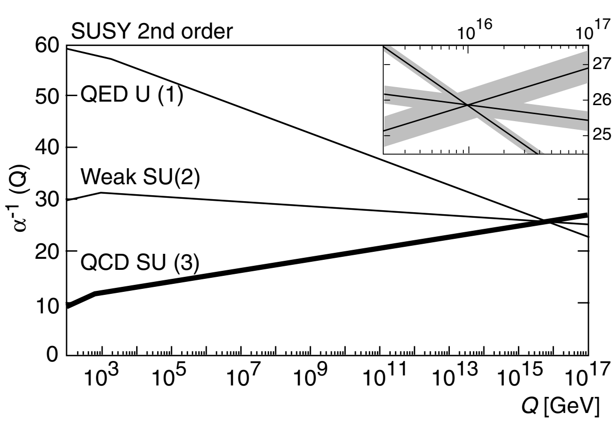


Fig. 1.8. Energy evolution of the different coupling constants of the QCD, weak and QED standard model taking into account the virtual effects of the SM particles and normalized to the MSSM $SU(5)$ coupling.

theory including gravitation. Many interesting attempts and proposals are available on the market.

The aim of this book is to present the developments of our understanding of strong interactions, and to concentrate on the exposition of its modern theory, called Quantum ChromoDynamics (QCD). Indeed, progress on strong interactions is important and necessary for making progress in the understanding of the physics beyond the SM.

2
The pre-QCD era

2.1 The quark model

- We know that hadrons have mainly strong interactions. However, the number of observed hadrons increases drastically in comparison with that of leptons. The classification of hadrons into multiplets has been facilitated by the discovery of *internal symmetries*, which play an important rôle for obtaining relations among masses, magnetic moments and couplings of the hadrons. The classification under the $SU(3)_F$ group (named *flavour* at present) [7] has been successful, where hadrons are characterized under their isospin I, hypercharge Y, baryon number B and strangeness S. Therefore, the pions are placed in the same pseudoscalar octet as the K, $\bar{K}$ and η, while the vector mesons ρ, ω, ϕ fill another octet, ... The splitting of hadron masses was expected, due to $SU(3)_F$ breaking that originated from strong interaction forces, whereas the $SU(2)$ isospin subgroup was found to be almost symmetric. This led to the concept of *charge independence*, which has played an important rôle in nuclear physics, where the proton and neutron form an $SU(2)$ doublet.
- However, none of the fundamental representations $SU(3)_F$ were realized by the observed hadrons, which led Gell-Mann and Zweig [8,9] to postulate that the observed hadrons, like the atoms, are not elementary, but are built by more elementary *quark*[1] constituents q having three flavours *up, down and strange*. Their charge Q in units of the one of the electron are:

$$Q_u = 2/3\,, \qquad Q_d = Q_s = -1/3\,. \tag{2.1}$$

In this picture, the mesons are bound states of quark–anti-quark, while the baryons are made by three quarks. The quarks internal quantum numbers are given in Table 2.1.

The $SU(3)_F$ decomposition into products of $\underline{3}$ and $\underline{3}^*$ representations gives for mesons:

$$\bar{q}q \;:\; \underline{3}^* \otimes \underline{3} = \underline{1} \oplus \underline{8} \tag{2.2}$$

and for baryons:

$$qqq \;:\; \underline{3} \otimes \underline{3} \otimes \underline{3} = \underline{1} \oplus \underline{8} \oplus \underline{8} \oplus \underline{10}\,, \tag{2.3}$$

[1] The name *quark* did not exist in the English dictionary, and may have been inspired from the following poetry *Finnengan's wake* of J. Joyce:

"Three quarks for Muster mark!
Sure he has'not got much of bark
and sure any he has it's all beside the mark."

However, *quark* is a well-known German word as it means curdy milk, but more commonly it means a mess.

Table 2.1. *Additive quark-quantum numbers*

Quark	u	d	s
Charge Q	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
Third component of isospin I_3	$\frac{1}{2}$	$-\frac{1}{2}$	0
Hypercharge Y	$\frac{1}{3}$	$\frac{1}{3}$	$-\frac{2}{3}$
Baryon number	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
Strangeness	0	0	-1

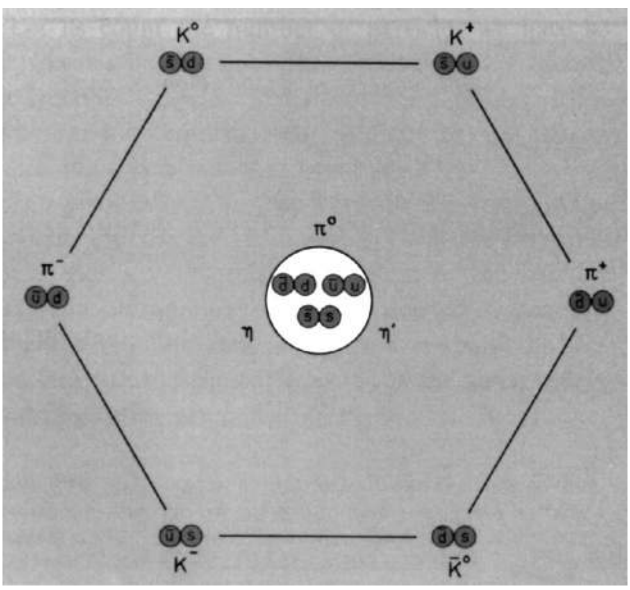


Fig. 2.1. The nine mesons built from the u, d, s quarks.

from which one can built a simple but complete Periodic Table of Hadrons. These classifications are given in Figs. 2.1 to 2.3. In this sense, the quark model was a modern version of the Sakata [10] model.

- Masses and mass-splittings of hadrons have been explained by using Gell-Mann–Okubo-like mass formulae [11], and by introducing the so-called *constituent* quark masses with the values [12]:

$$M_q \approx 300 \text{ MeV} , \tag{2.4}$$

and by assuming the quark-mass differences:

$$M_d - M_u \approx 4 \text{ MeV} , \qquad M_s - M_d \approx 150 \text{ MeV} . \tag{2.5}$$

- The compositeness hypothesis for the hadrons has been supported by the measurement of the proton magnetic moment which has a value of about 2.8 in units of $\mu_p = e\hbar/2M_p$, while it is expected to be unity from a point-like spin $1/2$ object.