Chapter 1

Introduction to High Energy Physics

THE OBJECT OF HIGH ENERGY PHYSICS IS the study the constituents of matter and their interactions at quantic and relativistic scales, conditions only reachable with very high energies. At these scales, matter and interactions are both described in terms of *particles*.

In this chapter, we give a general introduction to HEP: the context, history, achievements and challenges of this field of research.

1.1 Introduction

1.1.1 Units

Being both relativistic and quantic, the scope of HEP is reflected in terms of units [1].

1. Electric charges are counted in units of the *elementary charge*:

$$e = 1.602{,}176{,}6208(98) \times 10^{-19}\,\mathrm{C} \tag{1.1}$$

2. Terms of the dynamical equations are of order of the *reduced Planck constant*[1]:

$$\hbar = \frac{h}{2\pi} = 1.054{,}571{,}800(13) \times 10^{-34}\,\mathrm{Js} \tag{1.2}$$

3. Velocities are measured in units of the speed of light[2]:

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[1] $h = 6.626\,070\,040(81) \times 10^{-34}$ Js.

[2] The symbol c stands for *celerity*, an outmoded synonymous of velocity.

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$$c = 299{,}792{,}458\,\mathrm{m/s} \tag{1.3}$$

Units of energy are *electron-Volt*, or multiples:

$$1\,\mathrm{GeV} = 1.602{,}176{,}6208(98) \times 10^{-10}\,\mathrm{J} \tag{1.4}$$

1 eV corresponds to the kinetic energy that an electron gains when accelerated from rest in an electric potential of 1 V; moreover, 1 GeV roughly corresponds to the mass of the proton.[3] Momentum and mass are respectively measured in GeV/c and GeV/c^2; in practice however, the speed of light c is often omitted, as well as the $\hbar$ constant, both straightforward to recover into the formulae using dimensional analysis.

« *High Energy* » refers to the relation that can be derived using dimensional analysis between an energy E to a wavelength λ:

$$E = 2\pi\frac{\hbar c}{\lambda} \quad \text{or more simply} \quad E = \frac{2\pi}{\lambda} \tag{1.5}$$

i.e. probing high (low) energy scales implies probing low (high) distance scales.

1.1.2 Fundamental Interactions

Nowadays, nature is understood in terms of four *fundamental interactions*:

gravitation Gravitation describes interactions between objects due to their masses. Typical systems purely based on this force are solar systems, usually at large distance scales. Gravitation is by far the weakest interaction among the four; however, since masses are always positive, it is only cumulative and becomes therefore the dominant interactions from scales of $\mathcal{O}(1\,\mathrm{m})$.

electromagnetism Electromagnetism describes interactions between objects carrying an electric charge (so far, no magnetic charge has been observed). It is indeed the dominant force at scales from $\mathcal{O}(10^{-10}\,\mathrm{m})$ to $\mathcal{O}(10^{-3}\,\mathrm{m})$. Typical structures holding via the electromagnetic interaction are atoms and molecules; it also explains γ decay, as well as gaseous, liquid and solid states of matter.

strong nuclear interaction The strong (nuclear) interaction describes interactions of components and subcomponents of the atomic nucleus. "Nuclear" refers to the scales at which they take place, below $\mathcal{O}(10^{-14})$; the only macroscopic manifestation is α decay (emission of a nucleus of helium). In general, the study of the strong interaction requires very specific set-ups, as will be the case in this thesis.

weak nuclear interaction Finally, the weak (nuclear) interaction takes place only at small distance scales, similarly to the strong interaction. It is responsible for β decay (emission of an electron), which is crucial in the nucleosynthesis of stars, but no analogous system like planetary systems, molecules or nuclei may

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[3] $h = 938.272046(21)\,\mathrm{MeV}/c^2$.

be found for holding only thanks to the weak interaction. This is related to the fact that similarly to the strong interaction, it takes only place at scales of the nucleus, but is much weaker than the strong interaction. However, unlike the strong interaction, it does not only affect the constituents of the nucleus but all particles of matter.

At the scale of experimentation of HEP, gravitation is too weak to produce any measurable effect; moreover, it is extremely difficult to formalise a quantum theory of gravitation. Nowadays, only the three other interactions are physically experimented in HEP and mathematically described within the so-called SM. The SM will be the object of the next chapter.

1.1.3 Particles

In general, any object that can be regarded as *pointlike* can be called a *particle*:

- galaxies in the universe (cosmology),
- stars in a galaxy or planets in a solar system (astrophysics),
- molecules in a medium (statistical physics)
- atoms in a molecule (chemistry),
- nucleus in an atom or nucleons in a nucleus (nuclear physics),
- and partons in a proton (particle physics).

But properly said, Particle Physics concerns the *fundamental* and *composite* particles, i.e. the tiniest components and the sets made of these. It is in this sense that *particles* shall here be meant.
Essentially, these particles have two peculiar behaviours:

- Most of them are unstable and decay in a very short time (at most a small fraction of a second—see Fig. 1.1). Normal matter only consists of atoms made of stables particles: the protons, neutrons and electrons.
- When two particles collide *violently*, they may *produce* other particles.

The study of HEP consists in trying to understand these two behaviours. In particular, in this thesis, we are going to study an unstable particle, the b quark, which can be produced by colliding protons.

1.2 History

In this section, we recall some key steps in the history of the discovery of the fundamental constituents of matter, following both chronology and decreasing distance scale, as shown in Table 1.1.

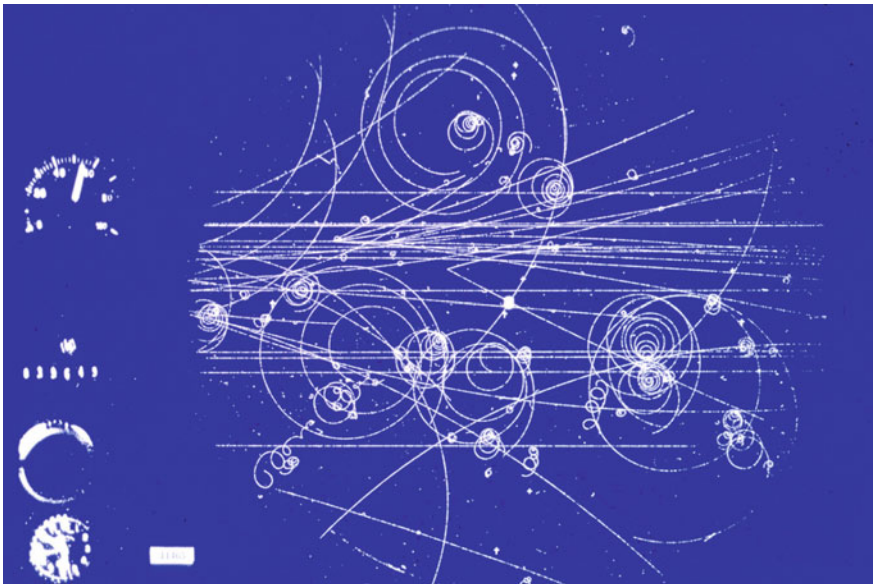

Fig. 1.1 This image from 1960 is of real particle tracks formed in CERN's first liquid hydrogen bubble chamber to be used in experiments. It was a tiny detector by today's standards at only 32 cm in diameter. Negatively charged pions with an energy of 16 GeV enter from the left. One of them interacts with a proton in the liquid hydrogen and creates sprays of new particles, including a neutral particle (a lambda) that decays to produce the "V" of two charged particle tracks at the centre. Lower-energy charged particles produced in the interactions spiral in the magnetic field of the chamber. The invention of bubble chambers in 1952 revolutionized the field of particle physics, allowing real particle tracks to be seen and photographed, after releasing the pressure that had kept a liquid above its normal boiling point. Figure reproduced with permission from European Organisation for Nuclear Research (CERN) [2]

Table 1.1 A few key figures relating the energy scale and the involved type of object. Note that 1 TeV represents approximately the kinetic energy carried by a domestic fly

Energy scale	Distance scale	Object
keV	10^{-10} m	Atom
MeV	10^{-13} m	Nucleus
GeV	10^{-16} m	Proton
TeV	10^{-19} m	Parton

1.2.1 Atomism (10^{-10} m)

The modern theory of atomism started with the publication of the book *Les Atomes* [3] in 1913 by Jean PERRIN, where thirteen different, compatible measurements of the *Avogadro number* were presented:

$$N_A \approx 6 \cdot 10^{23}\,\mathrm{mol}^{-1} \tag{1.6}$$

This number is the typical number of atoms to be found in a few centimeters. Matter is not a *continuum* but is made of small corpuscles.

1.2.2 Nucleus (10^{-13} m*)*

The existence of the electron was admitted but no such oppositely charged particle had been found. The atom was thought to be a diffuse, positive body in which the electrons, negative, would shelter (*Thomson model* or *plum-pudding model*). Between 1908 and 1913, the *golden-foil* experiment [4] by Sir Ernest RUTHERFORD, Hans GEIGER and Ernest MARSDEN highlighted the existence of a charged pointlike object—the *nucleus*—in atoms. The experiment (shown in Fig. 1.2) consists in bombing a golden foil gets with alpha rays, which can be found in naturally radioactive sources (like 238-uranium); according to the plum-pudding model, the radiation should have gone through the foil; however, they observed some alpha rays coming back. RUTHERFORD said: “It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you!” This was the first sign for the existence of a heavy, charged nucleus. The size of the nucleus was at most of the order of 10^{-13} m, since the energy of a natural source of alpha rays is around 5 MeV. This new model of the atom made of a small nucleus surrounded by an electronic cloud is called *Rutherford atom*.

1.2.3 Nucleus Structure (10^{-15} m*)*

From the 1950s at SLAC in the U.S. and later in the 1960s at DESY, the nucleus was probed with particle beams at an energy scale of the order of 100 MeV–1 GeV. Similarly to the golden-foil experiment, a nuclear target was bombed with a beam of electrons:

$$e + N \longrightarrow e + X \tag{1.7}$$

where e stands for *electron*, N for *nucleus* and X for some additional production. The nucleus itself was found to have a structure, make of pointlike *nucleons* (either protons or neutrons), arranged in a similar way to the structure of the electrons in the atom.

1.2.4 Nucleon Substructure (10^{-18} m*)*

At a still lower distance scale, i.e. with higher-energy beams, protons and neutrons also were found not to be pointlike, but with a substructure surprisingly different to

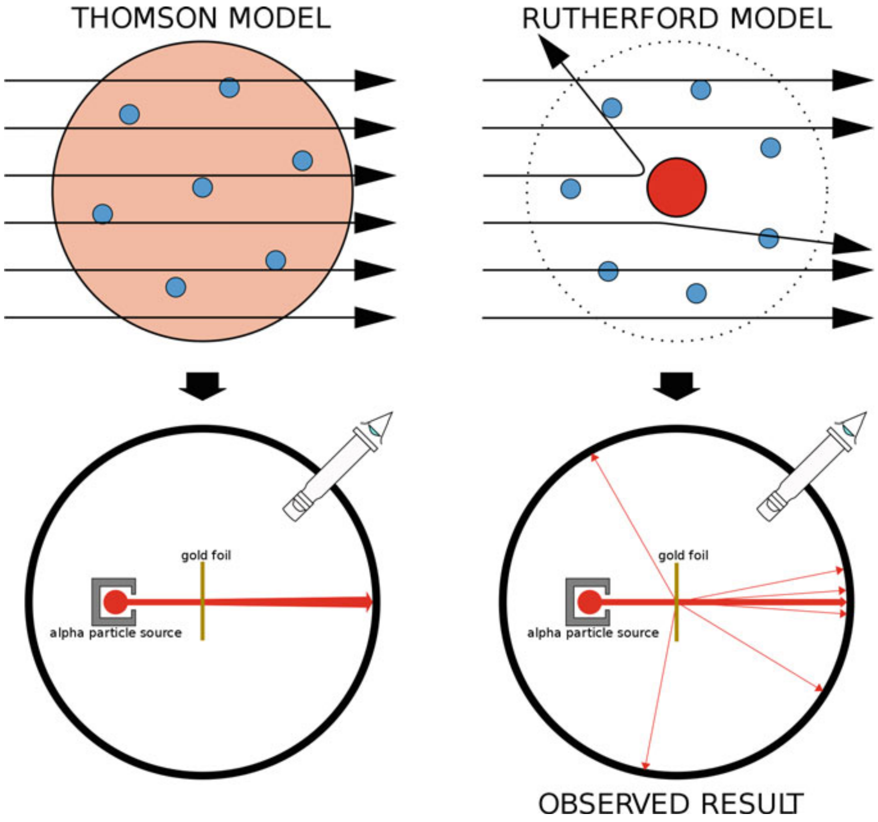

Fig. 1.2 A simple diagram illustrating the Geiger–Marsden experiment. The left column shows the scattering pattern that the experimenters expected to see, given the plum pudding model of the atom. The right column shows the actual results, along with Rutherford's new planetary model [5]

the atoms'. At that time, electrons were scattered on protons:

$$e + p \longrightarrow e + X \tag{1.8}$$

The results could be interpreted in two complementary ways:

1. the study the kinematics of the outgoing electron e led to the *parton model*, imagined by Richard FEYNMAN;
2. and independently the study of the symmetries of the hadronic production X led to the *quark* model, imagined by Murray GELL-MANN.

In the former, the *scattering* effects on the proton suggested pointlike subcomponents to exist, called *partons*, coherently moving without interacting with one another. In the latter, the existence of different subparticles, called *quarks*, could explain

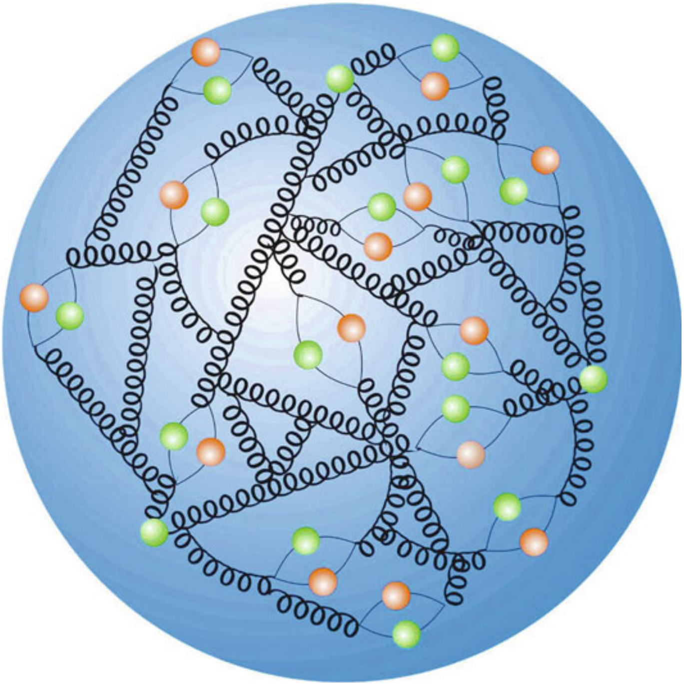

Fig. 1.3 On this artistic view, the proton is made of *quarks* (green), *antiquarks* (orange) and *gluons* (curly lines). There are three more quarks than antiquarks, called *valence quarks* (one can be found in the top, one in the right hand side, one in the bottom left). Quarks and antiquarks radiate gluons, themselves either radiating other gluons or decaying into a quark and an antiquark. *Source* DESY [6]

some *symmetries* among different types of particles. The two models were based on different observations and described the proton differently.

In the 1990s, at the HERA *ep* collider, at $E \sim 100\,\mathrm{GeV} \rightarrow 10^{-18}\,\mathrm{m}$, the H1 and ZEUS collaborations measured the content of the proton in terms of partons [7] (Fig. 1.3).

Since then, despite active searches, no new substructure has been found. However, six different *flavours* of quarks have been found. This thesis is dedicated to the study of one of them: the *b* quark.

1.3 Experimentation

We now discuss the experimental possibilities in HEP: first how to achieve the right conditions of experimentation, and what can exactly be measured.

1.3.1 Sources

Experimentation in HEP is limited in two aspects:

- Since most particles have a very short lifetime, one needs to find or set up sources of particles.
- Since particles have a very small size, very specific detectors needs to be set up.

One may distinguish three types of sources:

radioactive elements These can be found in nature or synthesised. This was how RUTHERFORD et al. first studied the atomic nucleus. Detection of particles are also performed.

cosmic rays Stars radiate particles, which scatter on molecules in the atmosphere. The *cosmic microwave background* also gives a picture of the universe when atoms were not yet bound together.

scattering experiments Accelerating particles and making them collide is another way to produce particles. In Part II, we are going to analyse data coming from a scattering experiment.

1.3.2 Observables

One distinguishes two observables: the *decay length* and the *cross section*. Any other fundamental parameter, e.g. the mass of the particles, is then extracted from the comparison of predictions and measurements.

Decay length. The *decay length* is the first observable that was measured in particle physics. All unstable particles, fundamental as well as composite, have a different lifetime.

Cross section. The second main measurable quantity in HEP is the *cross section*. Classically, the cross section is the overlapping area of the projections of the target in the transverse plane and the projectile particle. A first generalisation was performed when studying diffraction in optics, the cross section being then defined in terms of intensities rather than areas [8]. The concept was further extended in particle physics: particles having no clear borders, the cross section cannot be properly defined as a physical area; eventually, it is interpreted as a *rate* of scattering. Techniques to compute cross sections in HEP will be discussed in Chap. 2. In this thesis, we are going to measure a cross section.

1.4 Challenges

Despite the remarkable precision achieved in HEP experiments, many questions remained unanswered; for instance:

- gravitation is not described;
- the asymmetry observed between matter and antimatter in the universe is not explained;
- evidence for dark matter and dark energy abound in the universe (more in Appendix 1.A);
- the mathematical structure of the SM is unexplained, as well as its nineteen input parameters (see Chap. 2);
- calculations from the SM are not always analytically feasible, resulting in difficulties to produce predictions (see Chap. 2).

In this thesis

We present the measurement of the cross section of the inclusive *b* jet production in proton-proton collisions with the CMS experiment. The goal of this analysis is to test our knowledge at the *TeV scale*.

The first part is dedicated to present the context of the measurement. First, some elements of theory are given in Chap. 2 in order to discuss the current understanding of HEP and of proton-proton collisions; the notions of cross section and jet will be more rigorously detailed. This will be followed by a description of the CMS experiment, our experimental set-up, in Chap. 3. In Chap. 4, the MC techniques, abundantly used for calculations in HEP, are discussed, and some models used in the second part are already discussed. A review of *b* physics closes the first part in Chap. 5.

The second part is dedicated to the measurement itself. First the strategy of the analysis will be described in Chap. 6. Then Chaps. 7–8 contain the analysis itself. The comparison of the measurement to predictions is presented in Chap. 9.

Finally, a third part is composed of prospects and of various appendices.

1.A Dark Matter and Dark Energy

As we already stressed, gravitation is too weak to compete with other interactions, and is therefore not described in HEP. But the existence of dark matter and dark energy is a strong motivation for BSM.

1.A.1 Dark Matter

Several observations suggest more matter to be in the universe than the radiated light may let it believe, i.e. some type of matter that does not interact electromagnetically and that cannot be found on earth; this unknown matter is called *dark matter*.

Historically, the main technique to detect dark matter has been to compute the difference between the luminous mass and the dynamical mass. This can be done at different scales:

– star clusters [9],
– galaxy clusters [10]
– and galaxy dynamics [11].

More recently, *gravitational lenses* even allowed to map dark matter in the universe [12]; in addition, anisotropies in the *Cosmic Microwave Background* may be partly explained by the presence of dark matter [13, 14]. This list is not exhaustive, but these observations are pointing to an important missing piece of modern HEP.

1.A.2 Dark Energy

The *cosmological constant* is necessary to explain the observed expansion of the universe with the theory of general relativity [15]. Since it can be understood as a contribution to the energy, it is called *dark energy*. It would account for around two thirds of the content of the universe [16]; on the other hand, unlike baryonic and dark matter, it would fill the entire universe quite uniformly. Its nature is totally unknown; and its density is too low to be detected in experiments as of today.

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