CHAPTER 2

Theoretical Background

This Chapter will introduce the physical knowledge needed for the analysis carried out in the following chapters. Firstly a short overview of the standard model of particle physics is given, discussing the fundamental particles and their interactions. Special emphasis is put on the top quark as its properties are pivotal for the four-top process studied in this thesis. The final state and the production channels of the four-top process will be described in the last section of this chapter.

Unlike different areas of physics, it is not common to use S.I. units in elementary particle physics since energies, mass and, momenta scales encountered are tiny. For instance the cross-section usually is quoted in barns ($1\text{barn} \equiv 10^{-28}\text{m}^2$ [???]) with modern accelerators reaching cross-section up to fb. The system used instate is known as natural units where [kg,m,s] are replaced by [$\hbar$,c,GeV[1]]. To simplify the units $\hbar = c = 1$ will be used in this thesis. Thus, all momenta, energies, and masses have the same unit GeV whereas time, and length are given in terms of GeV^{-1}.

2.1 The Standard Model of Particle Physics

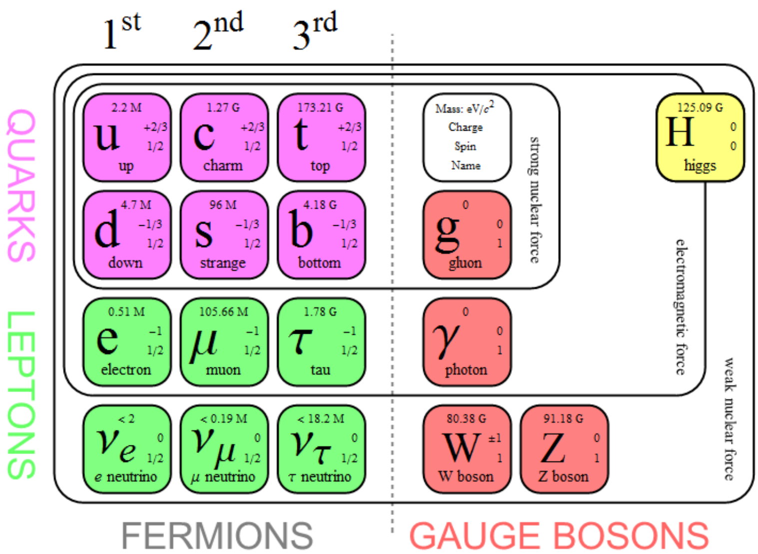


Figure 2.1: [???] Scheme of the standard model of particle physics. Particles that belong to the same type are depicted in the same color. The interaction of particles is indicated by plateaus where particles on the highest plateau only interact via the strong interaction and particles on the lowest obey all interactions. The weak nuclear force and the electromagnetic force are the two forces unified[???] in the SM to the electroweak force.

[1] GeV is the abbreviation for Giga electron volt where $1\text{GeV} = 1.602 \cdot 10^{-19}$ J

The standard model of particle physics (SM) embodies our current understanding of the fundamental constituents of the universe and their interactions. It is a renormalizable quantum field theory constructed from a number of profound theoretical ideas to describe the experimental data observed. As often the case for physical theories the SM is guided by the principle of symmetry. Its local gauge symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_\gamma$$

consists of the *colour* symmetry group $SU(3)_C$ and the symmetry group of *hypercharge* $SU(2)_W \times U(1)_\gamma$. The hypercharge and the colour charge are the charges related to the strong nuclear force and the electroweak force, respectively. Therefore, the SM contains two of the fundamental forces of nature. Gravity which is the third fundamental force can be neglected at the particle level scales.

The particles in the SM are all elementary particles i.e. they show no indication of substructure up to the current level of accuracy. All elementary particles can be categorized according to their spin statics. Particles of half-inter spin obeying the Fermi-Dirac-statics are called *fermions* while particles of inter spin are called *bosons* and obey the Bose-Einstein-statics.

Fermions are further subdivided into *quarks* and *leptons*. Quarks contrary to leptons can interact via the strong nuclear force. They come in 3 colours and 6 types called *flavors* $f = u, d, s, c, b, t$ called *up*, *down*, *charm*, *beaty* (or *bottom*), and *top*. Mathematically speaking quarks form 3 flavor doublets where the upper component has an el. charge of $Q = \frac{2}{3}$ and the lower an el. charge of $Q = -\frac{1}{3}$. From a physical point of view, this structure is reflected in three *generation* of quarks. The 2^{nd} and 3^{th} generation quarks have the same quantum number as the quarks from the 1^{th} generation but higher rest mass. In addition to the 6 quarks, there are 6 associated antiquarks that have the same mass but inverse quantum numbers. Experimentally it was observed that quarks only exist in bound states of quark-antiquark pairs called *mesons* or three quark or antiquark systems called *baryons*. The standard model explains this behavior by the hypothesis of *colour confinement*, which states that coloured objects are always confined to colour singlet states and thus are "courless". In the case of quarks, the process of confinement is often referred to as *hadronization*.

Similarly to quarks, the sixth leptons of the SM can be sorted into three doublets and generations, respectively. The lepton in the generation that is el. uncharged and massless[2] is called a *Neutrino*. It can be distinguished from its charged partner by its interaction with the electroweak force.

The forces in the standard model are mediated by *gauge bosons*[3]. The gauge boson associated with the strong nuclear force is the gluon. The gluon is a massless particle that carries colour charge. The electroweak force is mediated by three gauge bosons, two mass once called $W^\pm$ and Z bosons, and one massless boson called *photon*. The photon is the only gauge boson that does not carry its own charge and therefore can not self-interact.

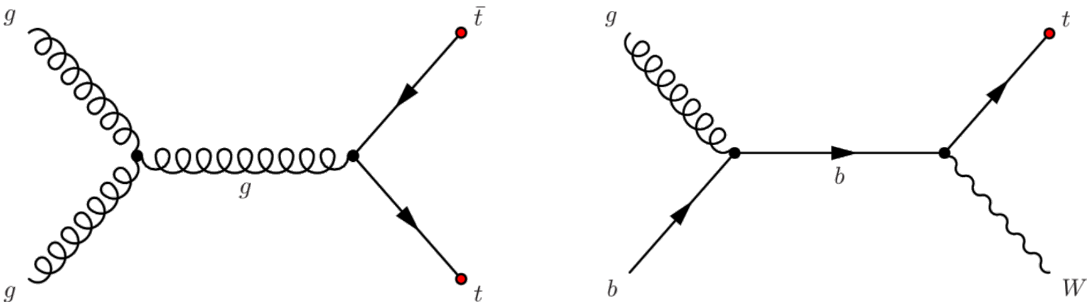
The standard model is summarized in Figure 2.1. The only particle not yet introduced in this picture is the Higgs boson. It can be interpreted as the excitation of the field predicted by the Higgs mechanism through which all other particles acquire their rest mass.

Even though the standard model is a remarkable achievement of modern science it's just that a model. It has several shortcomings for instance it provides no candidate for dark matter[???] nor explain the large matter-antimatter asymmetry in our universe.

[2] Neutrinos are only assumed to be massless in the standard model. The existence of neutrino oscillations indicate that they have to have at least a very mass.

[3] The term "gauge" indicates that theories describing the forces are invariant under local gauge transformations[???]

2.2 The Top Quark



(a) Top pair production

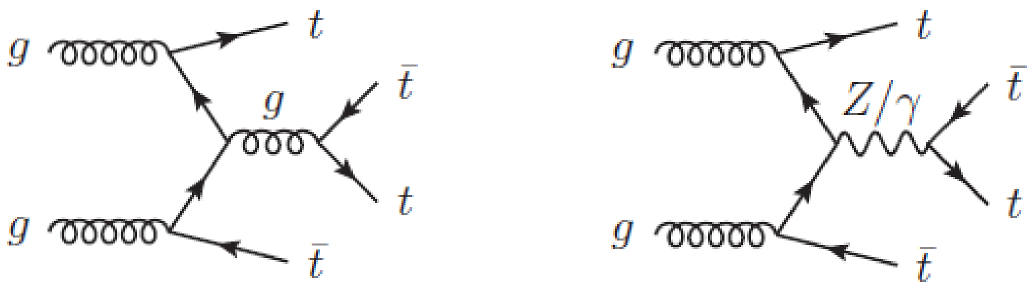
(b) Single top production

Figure 2.2: The two different categorizes of Top production

The top quark has been first discovered in proton-antiproton annihilations at the Fermilab Tevatron Collider in 1995 [???]. It has a charge of $Q = \frac{2}{3}$ and was expected to be heavy. In fact, it is was observed to be the most massive particle of the Standard Model with a mass of 173 ± 0.4 GeV[???]. Therefore, it is almost 40 times heavier than the next-lighter quark, the b quark. Owing to its large mass, the lifetime $\Gamma_{\text{top}} \approx 0.5 \cdot 10^{-24}$ s[PDG] of the top quark is very.
Since the lifetime of the top quark is a magnitude lower than the typical interaction of the strong force, the top quark decays faster than any hadronization process. Moreover, the matrix element governing the decay of the top quark is proportional to the mass difference between the top quark and the decaying product. Consequently, it decays with a branching fraction of almost 100% to a b-quark and a W^+, since the b-quark is much heavier than the quarks of the 1^{th} and 2^{nd} generation.
The production processes producing a top quark can be categorized into top-quark pair production and single top production. The processes in which the top is produced in pairs made up the main contribution of events in the discovery of the top-quark. This is because process producing single tops are governed by the electroweak interaction whereas top-antitop pairs are produced via the strong interaction, as can be seen in Figure 2.2. Thus, the first evidence for single top processes was published considerably later in 2006. An advantage of the single top production is that the transition matrix $|V_{\text{tb}}|^2$ can be measured directly.

2.3 The four Top-Quark Process

The studies carried out in this thesis are part of the four top-quark analysis carried out by the ATLAS collaboration at $\sqrt{s} = 13$ TeV. Due to the high mass of the top quark, this process is one of the energetically highest processes accessible at the Large Hadron Collider. It is a rare process making it both challenging to observe and interesting to study. Moreover, in many beyond the Standard model scenarios the cross-section of $t\bar{t}t\bar{t}$ ($\sigma_{t\bar{t}t\bar{t}}$) is enhancement. The most recent Next-to-leading order calculations of the SM cross-section predict $\sigma_{t\bar{t}t\bar{t}} = 11.97^{+18\%}_{-21\%}$ at at $\sqrt{s} = 13$ TeV. Two previous analyses by ATLAS and CMS of this process using 36fb^{-1} of 13 TeV data were carried out. The observed (expected) upper limits for the $t\bar{t}t\bar{t}$ cross-section are 41.7fb (20.8)fb and 49fb (19fb), respectively. The observed significances for the combination of both results are 2.8 and 1.0 standard deviations.



(a) (b)

Figure 2.3: [INTNOTE] Representative Feynmann diagrams for $t\bar{t}t\bar{t}$ at leading order in the SM.

The Feynman diagrams of three $t\bar{t}t\bar{t}$ production processes are shown in Figure 2.3. As mentioned in Section 2.2, the four tops will almost exclusively decay into a b quark and a W boson. The W boson can further decay either hadronically into quarks or leptonically into a charged lepton and a neutrino, while the b quark will hardoize. The branching ratios for the possible leptonic 'l' and hardronic 'h' decay combinations are shown in Figure 2.4 where the llhh category is subdivided depending on the charges of the leptons. These categories are used later on to define two different analysis channels. The $t\bar{t}t\bar{t}$ final state characteristics, therefore, are a high quark and b-quark multiplicity as well as a high number of neutrinos.

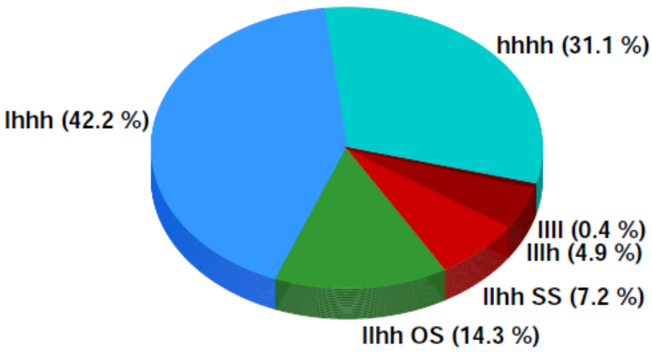


Figure 2.4: [INTNOTE] Branching ratio for the decays of four W bosons in the $t\bar{t}t\bar{t}$ process. Here 'l' indicate leptonically decaying W bosons and 'h' hadronically decaying once.