Muons in early ATLAS data: from first collisions to W+ W- production
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CHAPTER 1

Introduction to $W$-Pair Production at the LHC

1.1 Overview

In this thesis, we are going to explore the first data recorded by the ATLAS experiment at the LHC, CERN. We will thereby focus on the reconstruction and identification of muons. Particularly di-muon final states play an important role, both for the performance studies as well as for the physics analysis detailed in this thesis. This chapter discusses the underlying theory to the studies carried out in the subsequent chapters. After a brief introduction to the Standard Model we focus on the relevant physics processes for this thesis. Section 1.3 discusses the $J/\psi$ particle which plays a prominent role in the performance studies throughout chapters 4 and 5, while Section 1.4 details the underlying theory to the measurement of the $W^+W^-$ production cross section discussed in Chapter 6.

1.2 The Standard Model of Particle Physics

It is in the 70’s of the past century when numerous contributions of the leading physicists finally form a consistent theory which describes the elementary particles and their interactions, incorporating three of the four forces of nature. For the first time, the observed physics at the smallest distances was comprehensively described by a theoretical model. It structured and explained the zoo of elementary particles that had been discovered since J.J. Thomson’s discovery of the electron in 1897 and whose growth was dramatically boosted by the exploitation of the first particle collider experiments in the 50’s and 60’s of the twentieth century [2]. However, to fully size this breakthrough one needs to confront the numerous precise predictions of the model with the corresponding experimental findings. A phenomenal agreement between the measurements and the theoretical predictions verified the theory. It is for these reasons that it was given the name:
The Standard Model of Particle Physics (SM) [4, 6].

1.2.1 The Elementary Particles and Their Interactions

The Standard Model utilizes group theory to describe electromagnetism, as well as the two short-range nuclear forces, the weak and the strong force with the symmetry group $SU(3) \times SU(2) \times U(1)$. Gravity is not incorporated in this model. However, at the energy scales of interest, gravity is $O(10^{25})$ weaker than the weakest of the three incorporated forces, the weak force. Thus, gravitational effects can be neglected.

According to Noether’s theorem, a differentiable global symmetry has a corresponding conservation law [3]. The conserved quantities for the three forces are the electric charge $e$ in case of electromagnetism, the third component of the weak isospin $I_3$ for the weak force and color for the strong force.

Gauge Bosons

The generators of the three local symmetry groups are associated to gauge bosons that mediate the to each symmetry corresponding force. The photon ($\gamma$) mediates electromagnetism, the three gauge bosons $W^+$, $W^-$ and $Z$ are the carriers of the weak force while eight gluons mediate the strong force. The experimentally determined masses and electric charges of the gauge bosons are listed in Table 1.1. They follow the Bose-Einstein statistic and have an integer spin. A second category of particles in the Standard Model has half-integer spin, follows the Fermi-Dirac statistics and is consequently referred to as fermion.

<table>
<thead>
<tr>
<th>gauge bosons</th>
<th>$\gamma$</th>
<th>$W^\pm$</th>
<th>$Z$</th>
<th>$g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass [GeV]</td>
<td>0</td>
<td>$80.399 \pm 0.023$</td>
<td>$91.188 \pm 0.002$</td>
<td>0</td>
</tr>
<tr>
<td>electric charge</td>
<td>0</td>
<td>$\pm 1$</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1.1: The gauge bosons of the Standard Model are shown with their masses and electric charge. All values are taken from [1].

Quarks and Leptons

All matter in our universe is made of fermions. The elementary fermions are grouped into quarks and leptons. One distinguishes leptons that only interact weakly, the neutrinos ($\nu$), from charged leptons which can also interact electromagnetically. The color carrying quarks can interact via all three forces incorporated in the SM, allowing the formation of atoms. All atoms in the universe are composed of electrons ($e^-$) as well as up- and down-quarks ($u, d$). However, particle collider experiments revealed the existence of 2 copies with increasing particle masses of these so called first generation fermions. The charged lepton of the second generation, the muon, commonly denoted as $\mu$ plays an important
1.2 The Standard Model of Particle Physics

role in this thesis. It is the heavier brother of the electron, carrying about 200 times its mass. However, it is yet too light to decay hadronically. It decays weakly into an electron and the corresponding neutrinos, after a long lifetime of $\tau_\mu \approx 2.2 \mu s$. The long lifetime and the comparatively low energy loss via Bremsstrahlung due to its high mass, allow the muon of a given energy to penetrate matter far more deeply than electrons.

Particles carrying color charge can only be observed in bound-states, due to the color confinement. These bound-states are color neutral and called hadrons. The existing three colors and anticolors leave room for two different types of bound-states. Bound-states of three quarks, such as the proton ($uud$) or the neutron ($udd$) are referred to as baryons, while the bound-states of a quark-antiquark are named mesons. An example of the latter is the $c\bar{c}$ bound-state, named $J/\psi$, which is discussed in Section 1.3. The quarks and leptons of all three generations are listed in Table 1.2 together with their masses and electric charge. All particles have their corresponding antiparticles with the same quantum numbers and mass but opposite charge. They are commonly denoted with a bar.

<table>
<thead>
<tr>
<th>generation</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>quarks</td>
<td>mass</td>
<td>mass</td>
<td>mass</td>
</tr>
<tr>
<td></td>
<td>[MeV]</td>
<td>[GeV]</td>
<td>[GeV]</td>
</tr>
<tr>
<td>$u$</td>
<td>[1.7; 3.1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d$</td>
<td>[4.1; 5.7]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e$</td>
<td>0.5110 ± 0.0000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>[0; 2×10^-6]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c$</td>
<td>1.29^{+0.05}_{-0.11}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$s$</td>
<td>[0.08; 0.13]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.1057 ± 0.0000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>[0; 2×10^-9]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td>172.9 ± 0.6 ± 0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td>4.19^{+0.18}_{-0.06}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>1.7768 ± 0.0002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>[0; 2×10^-9]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>electric charge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−1/3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2: The fundamental fermions of the Standard Model are shown grouped into the three generations. The masses of the particles, or the corresponding mass ranges are given together with the electric charge. All values are taken from [1]. Some of the given values are rounded.

1.2.2 The Standard Model Higgs

Despite its predictive power, the Standard Model also shows various weaknesses like the introduction of 21 independent parameters, whose values are not predicted in the theory and have to be determined experimentally [5]. It also offers no explanation to why there are three generations of fermions, or how gravity fits in the picture. But the probably most striking incongruity lies in the origin of the elementary particle masses. The Standard Model allowed originally only for massless particles. Divergencies in the loop diagrams of massive particles break the essential renormalizability of the theory. It was extended by Peter Higgs and others to incorporate a mechanism that would give rise to the mass of the massive Standard Model particles, such as the heavy weak gauge bosons [9]. However,
this extension of the theory introduces an additional particle, the Higgs boson. Despite
the large efforts of the particle physics community in the last decades no experiment has
discovered the Higgs boson, to date. The latest efforts however, will bring an end to the
search of the Higgs boson in the near future, with the LHC experiments being designed to
either discover or rule out the Standard Model Higgs boson, see Section 2.3. Combining
the results of previous experiments and the latest findings sets limits on the SM Higgs
boson mass: $114.4 \text{ GeV} < m_H < 146 \text{ GeV}$ or $m_H > 476 \text{ GeV}$ [10,11].
The production cross section at the LHC \(^1\) as a function of the SM Higgs boson mass
is given in Figure 1.1(a). The four leading production processes are the gluon fusion
($pp \rightarrow H$), the vector boson fusion (VBF, $pp \rightarrow q\bar{q}H$) and the two Higgs boson radiation
processes ($pp \rightarrow WH, pp \rightarrow ZH$) that are depicted in Figure 1.2. Figure 1.1(b) displays the
possible decay channels of the SM Higgs boson with their predicted branching ratios. One
important decay channel to look for the Higgs boson is its decay into a pair of $W$-bosons,
i.e. $H \rightarrow W^+W^-$. In the leading production channel, where two gluons fuse to create a
Higgs boson, the cross section times the branching ratio for the process $pp \rightarrow H \rightarrow W^+W^-$
has been calculated to $\sigma \times \text{BR}(H \rightarrow W^+W^-) = (14.12^{+19.2\%}_{-15.1\%} \times 0.305) \text{ pb}^{-1}$ for a Higgs
boson with mass $m_H = 130 \text{ GeV}$ [66] \(^2\).

\[ \text{(a) SM Higgs boson production cross section} \quad \text{(b) SM Higgs boson branching ratios} \]

**Figure 1.1:** The expected SM Higgs boson production cross section as a function of the
corresponding Higgs boson mass is shown in (a) for a center of mass energy of 7 TeV. (b)
shows the branching ratios of the SM Higgs boson, again as a function of its mass. The
layout of the two plots taken from [66] was modified for this thesis.

\(^1\)The Large Hadron Collider is detailed in Section 2.2.
\(^2\)The errors on the cross section are given as the linear combination of the QCD scale, PDF and strong
coupling uncertainties.
1.3 The J/ψ Meson

The J/ψ was independently discovered in 1974 by the group of Burton Richter at the Stanford Linear Accelerator Center (SLAC) and the group of Samuel Ting from MIT at the Brookhaven National Laboratory (BNL) [7]. The discovery confirmed the existence of a predicted fourth quark, the charm quark (c) and was awarded with a Nobel Prize two years later.

The J/ψ is the first excited charmonium state, i.e. it has the second-smallest rest mass of all c̅c bound-states. However, since it is the lowest rest mass charmonium state with the same quantum numbers as the photon, its production rate is much higher than any other c̅c meson. Its rest mass has been measured to be \( m_{J/\psi} = 3096.92 \pm 0.01 \text{ MeV} \) [1]. The comparatively long mean lifetime of the J/ψ leads to a narrow average width of its mass distribution of \( \Gamma = 92.9 \pm 2.8 \text{ keV} \). One can distinguish three different J/ψ production mechanisms at hadron colliders:

- **the direct production**: The J/ψ is directly produced in the central collision, e.g. \( pp \rightarrow J/\psi \) in case of a proton-proton collider such as the LHC discussed in the subsequent chapter.

- **the prompt production**: The J/ψ is produced via a decaying excited charmonium state, i.e. for example \( pp \rightarrow \chi_c \rightarrow J/\psi + \gamma \), or \( pp \rightarrow \psi'_c + X \rightarrow J/\psi + X \), where \( X \) denotes any particle(s) created in the associated process. \( \chi_c \) and \( \psi'_c \) stand substitutional for the various c̅c bound-states of the corresponding type, i.e. \( \chi_c^0 \), \( \chi_c^1 \), \ldots, \( \psi(2S) \), \( \psi(3770) \), etc..

- **the non-prompt production**: Here, the J/ψ is produced in a weak decay of a B meson.

It is very difficult to distinguish the direct and prompt produced J/ψ’s experimentally in existing collider experiments. Figure 1.3(a) shows the inclusive J/ψ production cross figure. 1.2: The Standard Model tree-level Feynman diagrams for the leading SM Higgs boson production processes at hadron colliders are shown.
section in the two muon final state measured by the ATLAS collaboration in the central detector [8]. The results are compared to the findings of the CMS collaboration. The theoretical uncertainties from the unknown spin alignment of the $J/\psi$ are represented by the yellow band.

Only 70% of the $J/\psi$’s decay via the strong force leaving a share of 30% for the electromagnetic decay of the $J/\psi$’s [58]. The corresponding Feynman diagrams show the two possible decay processes in Figure 1.4. Naively, one would expect the strong force to dominate more clearly over the electromagnetic force in the decay. The strong decay of the $J/\psi$ is suppressed because of two reasons. $D$-mesons carry a single charm quark and would hence be a preferred decay product. However, their masses are larger than the $J/\psi$ mass and hence, this strong decay is not possible. The other reasons for a suppressed strong $J/\psi$ decay is the conservation of spin and color, requiring a decay into at least three gluons.

The majority of $J/\psi$’s still decay hadronically ((87.7 ± 0.5)%). However, a comparatively large fraction decays leptonically into an electron-positron or muon pair. The latter decay mode plays an important role in this thesis. The branching ratio $\text{BR}(J/\psi \rightarrow \mu^+\mu^-)$, i.e. the fraction of $J/\psi$’s that decay into a pair of muons is (5.93 ± 0.06)%. The invariant mass plot of two muons reconstructed in the ATLAS experiment, described in Section 2.3, is shown in Figure 1.3(b). Note that the width of the $J/\psi$ resonance is about 100 MeV and hence clearly dominated by the detector resolution.

![Figure 1.3: (a) production cross section (b) di-muon invariant mass](image)

Figure 1.3: The inclusive production cross section of $J/\psi \rightarrow \mu^+\mu^-$ measured by the ATLAS collaboration is shown in (a), while the $J/\psi$ resonance in the two muon invariant mass spectrum is shown in (b). In addition to the $J/\psi$, the next excited $c\bar{c}$ state called $\psi(2S)$ is visible around $m_{\mu\mu} = 3.69$ GeV. The plots are taken from [8,68].

Figure 1.5 shows the kinematic distributions of muons from $J/\psi$ decays \(^3\). As shown in (a) and (b), the decay products of the $J/\psi$ cover all space up to very large values

\(^3\)The distributions are based on Monte Carlo generated $J/\psi \rightarrow \mu^+\mu^-$ events as used in Chapter 5.
in pseudorapidity\textsuperscript{4}. Most of the muons have comparatively low transverse momenta. However, the spectrum reaches up to about 20 GeV as shown in (c). The corresponding distribution of the opening angle between the two muons is depicted in (d) and shows that the vast majority of the muon pairs have a sufficiently large opening angle which will be important to separately identified the two muons in the experiment. These features together with the clean, narrow resonance and the overall large production cross section makes the $J/\psi$ a very attractive tool for various physics and performance studies. Chapter 5 will exploit these features of the $J/\psi$.

\section*{1.4 $W^+W^-$ Production and Decay}

Measuring the production of $W$-pairs, i.e. $W^+W^-$ is an important test of the Standard Model. Moving from an originally only global symmetry to a local and hence gauge invariant symmetry requires the introduction of gauge fields. The gauge invariance is of outstanding importance since it makes the theory renormalizable. Renormalization assures that no divergencies occur in the theory.

The weak force is described in the Standard Model by the non-abelian gauge group $SU(2)$ in which the gauge fields quantize and the gauge bosons $W^+$, $W^-$ and $Z$ emerge. The most important consequence that arises from the non-abelian structure of the local $SU(2)$ symmetry are gauge boson self couplings, i.e. a $Z$-boson can couple to a pair of $W$-bosons (triple gauge boson coupling) and four $W$-bosons can connect in one vertex (quartic gauge boson coupling). The triple gauge boson coupling appears in a process, shown in Figure 1.6(c) for hadron colliders, that contributes to the overall production rate of $W$-pairs with approximately 10\% at the LHC. This significant contribution from the triple gauge boson coupling allows one to probe the non-abelian structure of the weak force in the SM and hence also provides the sensitivity to possible deviations from the SM. These deviations could either be observed in the measured production cross section or kinematic

\textsuperscript{4}Details on the coordinates are given in Section 2.3.1.
Introduction to \( W \)-Pair Production at the LHC

![Graphs showing kinematic distributions](image)

(a) pseudorapidity
(b) azimuthal angle
(c) transverse momentum
(d) opening angle

Figure 1.5: The kinematic distributions for muons from \( J/\psi \) decays are shown.

Distributions of the selected events and be possibly caused by yet unobserved particles in loop diagrams. Various measurements of these so called anomalous triple gauge boson couplings (aTGC) have been performed, e.g. [12,14,47]. However, no measurement showed evidence for the existence of anomalous couplings.

A profound knowledge of the \( W \)-pair production is however also essential for Higgs boson searches in the \( W^+W^- \) channel as it will be an irreducible and non resonant background that needs to be controlled. It is for this reason that we focus on a \( W^+W^- \) production cross section measurement in Chapter 6 of this thesis. Taking advantage of our work and findings in Chapters 4 and 5, we analyze the muon decay channel of both \( W \)-bosons. The branching fraction for a \( W \)-boson to decay into a muon is \((10.57 \pm 0.15)\%\) [1], thus about 1% of all produced \( W \)-pairs will decay into a \( \mu^+\mu^- \) final state.

We give in the following a summarizing overview over the existing cross section calculations as well as the present experimental determinations of the \( W^+W^- \) production cross section.
1.4.1 Cross Section Calculations

A first calculation of the $q + \bar{q} \rightarrow W^+ + W^−$ cross section in the Born approximation was published as early as 1979, four years before the discovery of the $W$-boson [15]. Real, virtual and radiative corrections were added with the first next-to-leading order (NLO) calculation published in 1993 [16]. Since then, QCD corrections and the gluon-fusion process $g + g \rightarrow W^+ + W^−$ have been calculated in addition [17, 18]. The tree-level Feynman diagrams for $W^+W^−$ production at hadron colliders are shown in Figure 1.6. The t-channel production in (a) is the leading production process with about 87% of the $W$-pairs being produced in this channel, while the gluon fusion contribution in (b) amounts to only 2.9%. The Z-exchange diagrams including a trilinear gauge boson coupling in Figure 1.6(d) cancel when summed over up- and down-type quark contributions in the triangular loop. The only contributing process to the $W^+W^−$ production including a vertex with the gauge boson self couplings is shown in Figure 1.6(c).

The latest NLO calculations give a total $W^+W^−$ production cross section of $\sigma_{W^+W^−} = (47.0 \pm 2.0) \text{ pb}$ at the LHC at a center of mass energy of $\sqrt{s} = 7 \text{ TeV}$ [18]. This is about a factor ten larger than the cross section of a SM Higgs boson with $m_H = 130 \text{ GeV}$ in the corresponding channel. The predicted leading order and next-to-leading order $W$-pair production cross sections as a function of the center of mass energy is listed in Table 1.3. The NLO corrections are significant.

\[\begin{array}{|c|c|c|}
\hline
\sqrt{s} [\text{TeV}] & \sigma_{LO}(W^+W^-) [\text{pb}] & \sigma_{NLO}(W^+W^-) [\text{pb}] \\
\hline
7 & 29.51 & 47.04^{+4.3\%}_{-3.2\%} \\
8 & 35.56 & 57.25^{+4.1\%}_{-2.8\%} \\
14 & 74.48 & 124.31^{+2.8\%}_{-2.0\%} \\
\hline
\end{array}\]

Table 1.3: The total $W$-pair production cross section is given for three center of mass energies relevant for LHC physics. The leading order calculation is compared to the next-to-leading order calculation. Renormalisation and factorization scales are set to the $W$-boson mass. Upper and lower limits are obtained by varying the scales by a factor of two in each direction. The numbers are taken from [18].

1.4.2 Experimental Results

Since the center of mass energy of the electron positron accelerator LEP was increased to $\sqrt{s} > 160 \text{ GeV}$ in the late 90’s to allow for the production of $W$-boson pairs, the theoretically calculated cross section for a $W^+W^- \ $production could first be experimentally verified and marked the first observation of trilinear gauge couplings. A good agreement with the SM predictions was found for various center of mass energies, as shown in Figure 1.7.

The first $W$-pair production cross section measurements on hadron colliders were performed at the Tevatron collider. At a center of mass energy of $\sqrt{s} = 1.96 \text{ TeV}$ the measured cross section $\sigma(W^+W^-) = 13.6 \pm 2.3(\text{stat.}) \pm 1.6(\text{sys.}) \pm 1.2(\text{lumi.}) \text{ pb}$ (CDF collabo-
Figure 1.6: The Standard Model tree-level Feynman diagrams for $W^+W^-$ production at hadron colliders are shown. Diagrams (c) and (d) contain trilinear gauge boson coupling vertices.

The most recent measurements are performed at the LHC running at a center of mass energy of $\sqrt{s} = 7$ TeV. The results will be discussed in Chapter 6.

1.4.3 Relevant Background Processes

As already mentioned, the $W$-pair production cross section will be measured in the di-muon, i.e. $\mu^+\mu^-$ final state with the corresponding neutrinos in Chapter 6. There are various physics processes with the same, or similar final states as well as processes that are a background to this final state, i.e. due to limited detector acceptance or miss reconstruction appear to have a di-muon final state. In the following, we list the relevant processes that contribute to the $W^+W^- \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$ background in the order of their production rates.
1.4 $W^+W^-$ Production and Decay

Figure 1.7: The total $W^+W^-$ production cross section in $e^+e^-$ collisions at LEP at center of mass energies of $\sqrt{s} = 161$ GeV to 207 GeV is shown. The band indicates the SM predictions. The figure is taken from [13].

Drell-Yan and $Z$-Boson Production

Drell-Yan processes are the largest source of di-muon events at the LHC. The ATLAS collaboration measured the production cross section times the branching fraction for the di-muon final state to be $\approx 1$ nb [19]. In the physics process, a quark and an anti-quark annihilate in the central collision. Via the exchange of a virtual photon or $Z$-boson, a lepton pair is created, such as $\mu^+\mu^-$. The corresponding Feynman diagram is depicted in Figure 1.8(a). The quark and anti-quark pair can also annihilate to create a $Z$-boson. The final state remains the same, but the invariant mass distribution of the lepton pairs from a $Z$-boson decay peaks at the $Z$-boson mass and is hence easily identified. The invariant mass spectrum of Drell-Yan processes in the two muon final state has been measured by the ATLAS collaboration and is shown in Figure 1.8(b) [76]. The $J/\psi$ and $Z$-boson resonance are the two most prominent peaks in the distribution originating from the comparatively large production cross sections.

Single $W$ Boson Production

The production of a single $W$-boson can also contribute to the $W^+W^-$ backgrounds, though only a single muon is created in the process, i.e. $W \rightarrow \mu \nu_\mu$. However, the large production rate of $W + X \rightarrow \mu \nu_\mu + X$, where $X$ indicates additional physics processes in the event that might also produce a muon, can still create a sizable background.
Introduction to W-Pair Production at the LHC

Figure 1.8: The Feynman diagram of the Drell-Yan process is shown in (a). The invariant mass spectrum of two muons in ATLAS is shown in (b). The plot is taken from [76].

contribution. The inclusive $W + \text{jets}$ cross section $^5$ with a muon final state has been measured by the ATLAS collaboration to be approximately 10 nb and is hence almost 5 orders of magnitude larger than the $W^+W^-$ production with the di-muon final state [19].

Top Quark

Top quarks are produced individually and in pairs at the LHC. Both physics processes have to be accounted for in a $W^+W^-$ background estimation. The single top production Feynman diagrams are given in Figure 1.9. The s-channel diagram marks the leading contribution in the single top production with $\sigma^{\text{NNLO}}(s\text{-channel}) \approx 65 \text{ pb}$ [67]. Top quarks decay into a $W$-boson and a bottom quark, i.e. $t \rightarrow W^+b$ and $\bar{t} \rightarrow W^-\bar{b}$. Hence, a $W^+$ and a $W^-$-boson are produced in $t\bar{t}$ events and mimic the SM $W^+W^-$ production. The cross section of $t\bar{t}$ production is larger than the production of single top quarks, the ATLAS collaboration measured $\sigma(t\bar{t}) = 176 \pm 5(\text{stat.})^{+14}_{-11}(\text{sys.}) \pm 8(\text{lumi.}) \text{ pb}$ [20] and it thus clearly dominates the $W^+W^-$ background contribution from top quarks. Figure 1.10 shows the leading gluon-fusion $t\bar{t}$ production process.

Di-Boson Production

Another background to the SM $W$-pair production arises from the production of $WZ$ and $ZZ$ di-boson pairs. These processes occur less often than the $W$-pair production in the

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$^5$The concept of jets will be discussed in Section 3.4.
Figure 1.9: The Feynman diagrams of the single top quark production processes at the LHC are shown.

Figure 1.10: The Feynman diagrams of the leading gluon fusion $t\bar{t}$ production at the LHC is shown, with the subsequent decay in the di-muon final state.

Standard Model, however, they can also mimic a $W^+W^-$ signal if part of the final states stay undetected in the experiment. However, since the di-boson production rates are very low compared to the other background sources it remains the smallest of all background contributions.
1.5 Summary

We gave an overview over the structure and the elementary particles of the Standard Model of particle physics. Besides the well established particles, the Higgs boson was briefly discussed as well. With the experimental setup introduced in the subsequent chapter, it is possible to test the SM at center of mass energies of 7 TeV and discover or rule out the SM Higgs boson. The measurement of \( W^+W^- \) production at this collision energy is an important contribution to both. Via the triple gauge couplings, it is sensitive to the non-abelian structure of the weak force and hence presents an important test of the Standard Model. In addition, the SM \( W^+W^- \) production will be an essential background that needs to be controlled in a search for the SM Higgs boson. At the Tevatron collider in the United States the Standard Model \( W \)-pair production has already been measured at the center of mass energy of 1.96 TeV and found to be in agreement with the Standard Model predictions. In this thesis, we will present a \( W \)-pair cross section measurement at 7 TeV, the highest center of mass energy reached yet in a collider experiment.

A precise measurement of the \( W^+W^- \) production cross section requires however a detailed understanding of the corresponding signatures in the experiment. We choose to measure the cross section of the process \( pp \rightarrow W^+W^- \rightarrow \mu^+ \nu_\mu, \mu^- \bar{\nu}_\mu \). The discussed \( J/\psi \) particle makes an excellent tool to study the identification of muons in the experiment.