In the modern picture of particle physics, every ordinary matter in our universe is made of twelve fundamental building blocks called elementary particles and their interactions are governed by four fundamental forces. Our best understanding on the relations between these elementary particles and fundamental forces is encapsulated in a theory called the Standard Model of Particle Physics.

The key actor of this thesis, the top quark, will be introduced in this chapter. Being one of the elementary particles of the Standard Model, we start in Section 1.1 with a brief introduction of the Standard Model and present other elementary particles that will become co-actors of this thesis. The top quark is then introduced in Section 1.2 with focus on its properties and the dominant top-antitop pair production in the hadron collider. Focusing on the main subject of this thesis, the single top quark production and its sensitivity to physics beyond the Standard Model will be discussed in Section 1.3.

1.1 The Standard Model of Particle Physics

The Standard Model [1, 2, 3, 4] is a Quantum Field Theory [5] that summarizes our current knowledge of the physics of elementary particles and their interactions. Developed in 70’s last century, it has become an established theory with its successful explanation on experimental results and precise prediction on all observed phenomena in particle physics.

The building blocks of the Standard Model are the twelve elementary particles that make up every matter in our universe. They are summarized in Table 1.1. These elementary particles are called fermions in the Standard Model as they are spin 1/2
particles following the Fermi-Dirac statistics. The fermions are categorized into three generations, each of them consists of two leptons and two quarks. The electron (e) and electron neutrino (νₑ) are the two lightest leptons; together with the two lightest quarks, the up (u) and down quarks (d), they form the first generation of the fermions. The four particles in the first generation have their own heavier relatives that are classified in the second and third generations. In view of the electric charge, electron as well as its heavier brothers, muon (μ) and tauon (τ) have −1 elementary charge equivalent to $-1.60 \times 10^{-19}$ Coulomb; while their partner neutrinos are charge neutral. Among the six quarks, the up, charm (c) and top (t) quarks carry the electric charge of +2/3 forming the so-called up-type quarks. On the other hand, the down, strange (s) and bottom (b) quarks with electric charge −1/3 make the family of the down-type quarks. The quarks carry a color charge in addition. The color confinement restricts the color-charged particles from being isolated singularly; therefore at lower energy quarks are bound together to form color-neutral particles called hadrons. The proton and neutron are two example hadrons.

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td>e</td>
<td>μ</td>
<td>τ</td>
</tr>
<tr>
<td></td>
<td>0.511 MeV</td>
<td>105.7 MeV</td>
<td>1.777 GeV</td>
</tr>
<tr>
<td></td>
<td>−1</td>
<td>−1</td>
<td>−1</td>
</tr>
<tr>
<td></td>
<td>νₑ</td>
<td>νₘ</td>
<td>νₜ</td>
</tr>
<tr>
<td></td>
<td>&lt; 2.2 eV</td>
<td>&lt; 0.17 MeV</td>
<td>&lt; 16 MeV</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Quarks</td>
<td>u</td>
<td>c</td>
<td>t</td>
</tr>
<tr>
<td></td>
<td>2.4 MeV</td>
<td>1.3 GeV</td>
<td>173 GeV</td>
</tr>
<tr>
<td></td>
<td>2/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>s</td>
<td>b</td>
</tr>
<tr>
<td></td>
<td>4.8 MeV</td>
<td>104 MeV</td>
<td>4.2 GeV</td>
</tr>
<tr>
<td></td>
<td>−1/3</td>
<td>−1/3</td>
<td>−1/3</td>
</tr>
</tbody>
</table>

Table 1.1: The elementary particles of matter with mass and electric charge.

There are four fundamental interactions of nature: the gravitational, electromagnetic, weak and strong interactions. A remarkable achievement of the Standard Model is the discovery of the fact that the electromagnetic, weak and strong interactions can be described in the subatomic level with the same mathematical structure called the gauge theory. A picture arising from the gauge theory is that the interaction of two particles can be effectively seen as an energy transfer in between, through the exchange of a mediator, the force carrier. Depending on the type of interaction, there

1The integration with the gravitation is still a challenge to physicists. However the gravitational interaction is negligible in the subatomic level given that its strength is negligible comparing to other three interactions.
are different force carries. They are photon, $W^\pm/Z$ and gluon in corresponding to the electromagnetic, weak and strong interactions, respectively. Those force carries are called denominators as they are spin 1 and follow the Bose-Einstein statistics. The photon and gluon are massless while the $W^\pm/Z$ bosons are on the other hand massive. Among these force carries, only the $W^\pm$ boson carries an electric charge of ±1. The gluon, as it acts exclusively on quarks, carries a color charge. The four interactions as well as their corresponding force carries are summarized in Table 1.2.

<table>
<thead>
<tr>
<th>Strength</th>
<th>Gravitational</th>
<th>Weak</th>
<th>Electromagnetic</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force carrier mass</td>
<td>graviton</td>
<td>$W^\pm$</td>
<td>$Z$</td>
<td>$\gamma$ (photon)</td>
</tr>
<tr>
<td>mass</td>
<td>0</td>
<td>80.4 GeV</td>
<td>91.2 GeV</td>
<td>0</td>
</tr>
<tr>
<td>electric charge</td>
<td>0</td>
<td>±1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 1.2:** The four fundamental interactions of nature and their corresponding force carriers. The strengths are shown relative to the electromagnetic force between two $u$ quarks separated by a distance of $10^{-18}$ m. Graviton is a postulated particle in analogy with those for the other three interactions.

The successful integration of the three fundamental interactions of nature with the gauge theory came with a controversial statement in the early development of the Standard Model: the fermions and the $W^\pm/Z$ bosons are massless. This issue was resolved by a proposed mechanism (the Higgs mechanism) through which the $W^\pm/Z$ bosons acquire masses in the process of the spontaneous symmetry breaking in the gauge theory. As a result, the Higgs mechanism predicts an additional boson (the Higgs boson) in the Standard Model and consequently the fermions receive their mass via the interaction with the underlying Higgs field.

The triumph of the Standard Model came from the fact that the hypothetical particles in the model were revealed by experiments one after one. The observation of the $b$ quark [6] and the $\tau$ lepton [7] confirmed the existence of the third generation fermions. Furthermore, the discovery of the $W^\pm$ and $Z$ bosons in 1983 [8, 9] with astonishing agreement on their predicted mass made a strong commitment to the foundation of the Standard Model. With those successful achievements, the existence of the Higgs boson was generally believed and expected for a long while within the physics community. In July 2012, when the two experiments at the LHC announced their discovery of a new type boson with properties compatible with the Higgs boson [10, 11], the Standard Model showed again its prediction power.
1.2 Top Quarks in Hadron Colliders

In order to explain the CP-violation in the Standard Model, Makoto Kobayashi and Toshihide Maskawa proposed the third generation of quarks in 1973 [12]. In 1975, when Haim Harari made the first statement on the six quarks model of the hadron spectrum [13], the names of “top” and “bottom” of the two third-generation quarks were introduced to reflect the fact that the two were the “spin-up” and “spin-down” components of a weak isospin doublet. Following the observation of the bottom quark in 1977, the existence of the top quark has been expected for a long while. With the mass of 173.5 GeV [14], it is by far the heaviest elementary particle in the Standard Model. Thus, the production of it requires high energy. Due to this reason, the top quark is for the first time observed by the CDF and D0 collaborations at Tevatron in 1995.

In view of its large mass, the top quark plays an essential role in the Standard Model and various theories beyond. Following the top quark discovery, main interest around this heaviest SM particle is to measure its properties in a high precision. Since the top quark has a very short lifetime, information of those properties are directly imprinted in the decay particles of the top quark and can be directly measured in the hadron colliders.

As of today, top quarks are produced at the Tevatron and the LHC. Tevatron, a proton-antiproton collider, was operated at a center-of-mass energy of $\sqrt{s}=1.96$ TeV with a luminosity of $L=10^{32}$ cm$^{-2}$ s$^{-1}$. Before its shutdown in 2011, it has delivered about 10 fb$^{-1}$ integrated luminosity of data to the CDF and D0 experiments. Being the successor of the Tevatron, the LHC started its full operation in late 2009$^2$. Unlike the Tevatron, it’s a proton-proton collider. It has been operated at a larger centre-of-mass energy of $\sqrt{s}=7$ TeV and $\sqrt{s}=8$ TeV in 2010/11 and 2012, respectively, with luminosity almost 2 magnitudes higher than Tevatron. In the years to come, the LHC will be operated at $\sqrt{s}=14$ TeV as its designed collision energy.

With higher centre-of-mass energy and luminosity, the top quark production rate at the LHC is significantly increased. The theoretical predictions on the particle production cross sections at the Tevatron and the LHC are shown in Figure 1.1. In terms of the top quark production, it is nearly 2 order of magnitudes higher at the LHC than at the Tevatron.

In the hadron collider, top quarks can be produced in two different ways. The primary is the top-antitop quark ($t\bar{t}$) pair production through the strong interaction; while the other is the single top quark production via the electroweak interaction. This thesis will focus mainly on the physics around the single top quark production, the main interests of which will be discussed in Section 1.3. For the moment, we will discuss briefly few top quark properties relevant to our studies as well as its main production.

---

$^2$The first operation of LHC was actually in September of 2008 followed by an accident causing a year-long break for the recovery.
Figure 1.1: Predictions for cross sections at the Tevatron and the LHC. Discontinuities in the curves come from the differences between proton-antiproton and proton-proton collisions. Figure taken from [15].
Chapter 1. Single Top Quark Production at the LHC

In the hard scattering of two colliding protons, top quarks are mostly produced in $t\bar{t}$ pairs through the strong interactions between partons. Using the parton model, this process can be illustrated schematically as Figure 1.2. The figure shows a collision of two energetic protons $P_1$ and $P_2$ with momentum $p_1$ and $p_2$ respectively. The hard scattering of the two protons can be seen as interaction between two partons from the protons. The probability of finding parton $i$ ($j$) carrying momentum fraction $x_1$ ($x_2$) in proton $P_1$ ($P_2$) is described by $f_i$ ($f_j$), the parton distribution function (PDF). The universal PDFs are not predicted by theory, but have been measured in experiments and can be evolved to the appropriate scale at which the proton is effectively probed. Therefore, the PDFs have an extra dependency on the factorization scale $\mu_F$, which connects the PDFs with the partonic cross section $\hat{\sigma}_{ij\rightarrow t\bar{t}}$ that can be calculated in perturbative QCD.

$$\sigma_{P_1P_2\rightarrow t\bar{t}} = \sum_{i,j=q,g} \int_0^1 dx_1 dx_2 f_i(x_1, \mu_F) f_j(x_2, \mu_F) \hat{\sigma}_{ij\rightarrow t\bar{t}}(x_1, x_2, m_t, \alpha_s(\mu_R), \mu_F)$$

In perturbative QCD, the partonic cross section $\hat{\sigma}_{ij\rightarrow t\bar{t}}$ has additional dependency on the top quark mass $m_t$ and $\alpha_s(\mu_R)$, the coupling constant in QCD with dependency on the renormalization scale $\mu_R$ [16].

To avoid spoiling the QCD perturbative calculation, a commonly used convention is to set both $\mu_F$ and $\mu_R$ to the order of the hard-scaling energy characterizing the

\[\text{Figure 1.2: The top quark pair production of a hard scattering in the parton model.}\]
production process, which is \( m_t \) for the top quark production. With \( \alpha_s(m_t) < 1 \), the partonic cross section can be expanded in a fixed-order series in \( \alpha_s \) as

\[
\hat{\sigma}_{ij \rightarrow tt} = \alpha_s^2 \left[ \hat{\sigma}_{ij \rightarrow tt}^{(0)} + \alpha_s \hat{\sigma}_{ij \rightarrow tt}^{(1)} + \alpha_s^2 \hat{\sigma}_{ij \rightarrow tt}^{(2)} + \cdots \right]
\]  

(1.2)

where the first term in square brackets is referred to as leading-order (LO), the second term next-to-leading-order (NLO), the third term next-to-next-to-leading-order (NNLO), and so on.

Each term of Equation 1.2 can be calculated using the Feynman diagrams and the Feynman rules [16]. Example Feynman diagrams contributing to the LO term are illustrated in Figure 1.3.

![Feynman diagrams](image)

**Figure 1.3:** Feynman diagrams contributing to the leading order (LO) \( t\bar{t} \) productions via (a) gluon fusion and (b) quark-antiquark annihilation.

In LO, \( t\bar{t} \) events are only produced by the interactions of either two gluons (gluon fusion) as in Figure 1.3(a) or two quarks (quark-antiquark annihilation) in Figure 1.3(b); the quark-gluon interactions happen only in NLO. Some examples of the NLO contributions to the \( t\bar{t} \) production are shown in Figure 1.4.

As a physical observable, the total cross section \( \sigma_{P_1 P_2 \rightarrow t\bar{t}} \) should not depend on the choice of the scales; but in the QCD perturbative calculation it does. One reason is that the calculation of Equation 1.2 is usually truncated to certain fixed order, and the truncated part has dependency on \( \alpha_s(\mu_R) \). Possible deviations due to the choice of the scales and the PDFs are usually evaluated as theoretical uncertainties.

Theoretical calculations up to NLO have been available a while ago. Going higher to NNLO, the amount of Feynman diagrams makes the QCD calculation a challenging task. In the meantime, the cross section accounting NNLO can only be calculated approximately [17]. Through out this thesis, we quote the \( t\bar{t} \) cross section of
Chapter 1. Single Top Quark Production at the LHC

Figure 1.4: Feynman diagrams contributing to the next-to-leading order (NLO) \( \bar{t}t \) productions.

\[
\sigma_{\bar{t}t}(\sqrt{s} = 7 \text{ TeV}, m_t = 172.5 \text{ GeV}) = 166.8^{+17.3}_{-18.4} \text{ pb}
\] (1.3)

from the approximate NNLO calculation \cite{18} and note that the uncertainty taking into account contains the variations on the QCD scale, PDF and the top quark mass\(^3\), and results in an order of 10%.

Contributions from different partonic reactions at the Tevatron and the LHC were also studied by \cite{19}. Given the momentum fractions \( x_1 \) and \( x_2 \) are relatively high at Tevatron, about 85% of \( \bar{t}t \) production is coming from the quark–antiquark annihilation (\( q\bar{q} \rightarrow \bar{t}t \)) followed by \( \sim 15\% \) contribution from the gluon fusion (\( gg \rightarrow \bar{t}t \)), while the quark–gluon reaction is only at the percent level. In contrast, \( x_1 \) and \( x_2 \) are small with the high center-of-mass energy of the LHC. Thus, the gluon fusion at the LHC contributes nearly 90% of the \( \bar{t}t \) production followed by the quark–antiquark annihilation, and the quark-gluon reaction is also at the percent level.

Measurements on \( \bar{t}t \) cross section were performed by experiments at the Tevatron and the LHC. Results are summarized in Figure 1.5. Within the uncertainty, those measurements show an agreement with the Standard Model prediction.

1.2.2 Decay

In the Standard Model, the only two-particle decays of the top quark which are possible to lowest order are \( t \rightarrow bW^+ \), \( t \rightarrow sW^+ \) and \( t \rightarrow dW^+ \). Their rates are proportional to

\(^3\)We will discuss in Section 1.2.3 that the theoretical prediction on the \( \bar{t}t \) cross section depends on the top quark mass given as a parameter in the calculation.
Taking the intermediate value depends on the choice of the QCD renormalization scheme. With its short yield’s decay width, it is reasonable to choose a scheme such that the top quark is treated in the Standard Model, the top mass is one of the parameters in the theory. The top quark decay and can be precisely measured.

Figure 1.5: Experimental measurements on the $t\bar{t}$ cross section at $\sqrt{s} = 1.8$ and 1.96 TeV by CDF and D0, and $\sqrt{s} = 7$ TeV by CMS and ATLAS. Figure taken from [14].

the squares of the CKM matrix elements $|V_{tq}|^2$ where $q = b, s, d$, respectively. Using the unitarity of the CKM matrix, the analysis of data from weak decays of hadrons yields $0.9990 < |V_{tb}| < 0.9992$ which implies that the Standard Model top decay is dominated by the process of $t \to bW^+$. Taking the intermediate $W$ boson to be on-shell and neglecting the mass of the $b$ quark, one gets the top decay width to the Born approximation:

$$ \Gamma_t \equiv \Gamma_t(t \to bW) = \frac{G_F}{8\pi\sqrt{2}} m_t^3 |V_{tb}|^2 \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + 2 \frac{m_W^2}{m_t^2}\right) $$  \hspace{1cm} (1.4)

where $G_F$ is the Fermi constant. Using $m_t = 171$ GeV and $m_W = 80.40$ GeV, Equation 1.4 gives the approximate top decay width of 1.44 GeV. Thus the average proper lifetime of the top quark to be $\tau_t = 1/\Gamma_t \simeq 5 \times 10^{-25}$ seconds which is an order of magnitude smaller than the hadronization time $\tau_{had} = 1/\Lambda_{QCD} \approx 3 \times 10^{-24}$ seconds. It means that the top quark will mostly decay before the QCD hadronization takes place; therefore it’s properties will be imprinted in the final state particles of the top quark decay and can be precisely measured.

1.2.3 Mass

In the Standard Model, the top mass is one of the parameters in the theory. The value depends on the choice of the QCD renormalization scheme. With its short decay width, it is reasonable to choose a scheme such that the top quark is treated as a free fermion. The top mass definition in this scheme is called pole or on-shell...
mass. Due to the perturbative calculation of QCD, the pole mass has an ambiguity of $\mathcal{O}(\Lambda_{\text{QCD}}) \sim 200$ MeV.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig_1_6}
\caption{Theoretical $t\bar{t}$ cross section with dependency on the top quark mass calculated for LHC at center-of-mass energy of 7 TeV. The central value of the theoretical prediction is presented as the continuous sold curve. The cross-hatched area around the central value shows the scale uncertainty, while the PDF uncertainty is added around with the filled area. Two measurements by CMS and ATLAS experiments are also shown. The horizontal bars on the measurements reflect the uncertainty in the measured top mass. Figures taken from [20].}
\end{figure}

While choosing a different renormalization scheme, one ends up with a different value of the top mass. For example, the top mass derived with a so-called $\overline{\text{MS}}$ scheme is known to be about 10 GeV lower than the pole mass. Because of this, theoretical predictions on physical observables, e.g. the $t\bar{t}$ cross section, are usually evaluated as a function of the top quark mass. In Figure 1.6, theoretical $t\bar{t}$ cross section is presented with the dependency on the top quark mass.

Combining the direct measurements performed by the Tevatron and LHC experiments, the up-to-date top quark mass referred by the Particle Data Group (PDG) is $173.5 \pm 0.6^{\text{(stat.)}} \pm 0.8^{\text{(syst.)}}$ GeV [14]. This value is generally assumed to be the pole mass. Strictly speaking, the mass measured in these direct measurements is the mass used in the Monte Carlo generator. The relation between the Monte Carlo generator mass and the pole mass has an uncertainty of $\sim 1$ GeV [21], which is at the same level of the measurement uncertainty.

One loop QCD corrections on the $W$ boson mass have quadratic and logarithmic dependencies on the top quark mass and the Higgs boson mass, respectively. Hence, precise measurements on the top quark mass can already set the constrain on the Higgs boson mass. Figure 1.7 combines the precise mass measurements of the $W$ boson and top quark to set the constrain on the Higgs boson mass and it overlaps with
1.3 Single Top Quark Production

In addition to the $t\bar{t}$ production discussed in Section 1.2.1, the top quark can also be produced through the weak interactions during the hard scattering. In this process, only one top quark is produced thus it is usually referred as the “single-top” production. In the Standard Model, the top quarks here are produced in charged current interactions via the $Wtb$ vertex, which contributes to the scattering matrix-element by the factor

$$-i\frac{g_w}{\sqrt{2}}|V_{tb}|\gamma^\mu(1-\gamma^5)$$

(1.5)
where \( g_w \) is the electroweak coupling constant, \( |V_{tb}| \) the CKM matrix element describing the strength of the electroweak coupling between the \( b \) and \( t \) quarks through the charged current \( W^{\pm} \), and \( \gamma^\mu(1 - \gamma^5) \) the vector-minus-axial-vector (V-A) structure indicating the electroweak interaction is left-handed\(^4\). As a result, the single top quark production cross section is directly proportional to \( |V_{tb}|^2 \).

Based on the way the \( W \) boson is involved in the reaction, the single-top production can be categorized into three production modes naming the \( t-, s- \) and \( Wt- \)channels. They are discussed in the following.

### 1.3.1 The \( t- \) and \( s- \)channels

In the \( t- \)-channel the top quark is produced via the exchange of a virtual, space-like \( W \) boson \( (q_W^2 < 0 \text{ GeV}^2) \) where \( q_W \) is the four-momentum of the \( W \) boson, while the \( s- \)-channel is processed by changing a virtual, time-like \( W \) boson with \( q_W^2 > (m_t + m_b)^2 \).

The leading order Feynman diagrams of these two modes are illustrated in Figure 1.8 and Figure 1.9 for \( t- \) and \( s- \)channels, respectively.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{feynman_diagrams.png}
\caption{Leading order Feynman diagrams for single-top \( t- \)channel production in (a) \( 2 \to 3 \) and (b) \( 2 \to 2 \) processes.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{feynman_diagrams.png}
\caption{Leading order Feynman diagrams for single-top \( s- \)channel production.}
\end{figure}

In the QCD calculation, the treatment of the \( b \) quark involved in the reaction initial

\footnote{The term \( 1 - \gamma^5 \) comes from the Dirac projection operator \( P_L = \frac{1}{2}(1 - \gamma^5) \) which projects the fermion field into its left-hand component. The left-handed feature of the electroweak interaction provides the theoretical explanation to the parity symmetry violation.}
1.3. Single Top Quark Production

state leads to two LO schemes in the $t$-channel. Figure 1.8(a) is the so-called 4-flavor scheme where (anti)proton is considered to be composed of only four light quarks ($u$, $d$, $c$, and $s$); the $b$ and $\bar{b}$ quarks arise from the splitting of a virtual gluon into nearly collinear $b\bar{b}$\textsuperscript{5}. The cross-section calculation with this scheme is of the order $\alpha_s \ln(m_t^2/m_b^2)$. Additional gluon radiations add contributions to the total cross section proportional to the higher powers of $\alpha_s \ln(m_t^2/m_b^2)$. Thus $\alpha_s \ln(m_t^2/m_b^2)$ serves as the expansion variable for the perturbative calculation in QCD. Unlike $\alpha_s$ in Equation 1.2, this expansion variable is close to 1 which makes the perturbative calculation unreliable.

A general approach to tackle this issue is to sum up the logarithmically enhanced terms into a $b$-quark PDF, which is perturbatively derived from the gluon distribution function. This approach leads to the 5-flavor scheme as illustrated in Figure 1.8(b). In the 5-flavor scheme, the process in Figure 1.8(a) becomes the NLO QCD contributions to the LO cross section.

The NLO cross sections for both $t$- and $s$-channels have been calculated by [23]. Using the soft-gluon resummation technique, the NNLO correction can be approximated with accuracy up to the next-to-leading logarithm (NLL) [24, 25] and the next-to-next-to-leading logarithm (NNLL) [26, 27].

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t$ ($\bar{t}$)</td>
<td>$t$</td>
</tr>
<tr>
<td>$t$-channel</td>
<td>2.08$^{+0.00}_{-0.04}$ ± 0.12</td>
<td>41.7$^{+1.6}_{-0.2}$ ± 0.8</td>
</tr>
<tr>
<td>$s$-channel</td>
<td>1.046$^{+0.002}_{-0.010}$ +0.060</td>
<td>3.17 ± 0.06$^{+0.13}_{-0.10}$</td>
</tr>
<tr>
<td>$Wt$-channel</td>
<td>0.28 ± 0.04$^{+0.02}_{-0.04}$</td>
<td>7.8 ± 0.2$^{+0.5}_{-0.6}$</td>
</tr>
</tbody>
</table>

Table 1.3: Approximate NNLO cross-section of the three single-top production modes at the Tevatron ($\sqrt{s} = 1.96$ TeV) and at the LHC ($\sqrt{s} = 7$ TeV). For LHC, cross sections corresponding to exclusive $t$ and $\bar{t}$ productions are shown separately to present the charge asymmetry in the $t$- and $s$-channels. The two uncertainties correspond to the scale variation and the PDF uncertainty, respectively.

Table 1.3 summarizes the approximate NNLO cross-section for both $s$- and $t$-channels at the Tevatron and the LHC. At both the Tevatron and the LHC, the $t$-channel is the most important one since its cross section is the largest among the three single-top production modes. The $s$-channel in the Tevatron yields the second largest contribution, while it is the smallest at the LHC due to the fact that the $\bar{u}$ and $\bar{d}$ at the initial states have to come from the quark-gluon sea of the proton.

One noticeable feature in the $t$- and $s$-channels at the LHC is the asymmetric production of top and antitop quarks which can be understood as a consequence of the fact that there are more valence $u$ than $d$ quarks in the proton-proton collisions. Using the $t$-channel as an example, the dominant partonic processes for $t$ quark production

\textsuperscript{5}It is why the $t$-channel reactions are sometimes called the ‘$W$–gluon fusion’ in literature.
involve $u$ or $\bar{d}$ in the initial states; while the production of $\bar{t}$ quark requires $\bar{u}$ or $d$. Assuming that the $\bar{d}$ and $\bar{u}$ quarks have to come from the quark-gluon sea of the protons and they have a similar probability density, the ratio between $t$ and $\bar{t}$ productions is approximately the ratio between the valence $u$ and $d$ quarks of the two protons. In the proton-antiproton collision at the Tevatron, the $t$ and $\bar{t}$ production is symmetric taking into account the $d$ and $\bar{u}$ valence quarks of the antiproton.

### Experimental measurements

Observations of the single top production in $t$- and $s$-channels were firstly reported at the Tevatron in 2009 [28, 29]. Due to the relatively small signal significance and similar kinematic signatures with backgrounds, precise cross section measurement requires more sophisticated data analysis techniques to be developed. In both CDF and D0, the measurement employes various multivariate data analysis techniques for discriminating signal from backgrounds. The cross section measurements by CDF [30] and D0 [31] collaborations using integrated data luminosity of 7.5 fb$^{-1}$ and 5.4 fb$^{-1}$, respectively, are summarized in Table 1.4. Both measurements are in an agreement with the Standard Model expectation with top quark mass of 172.5 GeV. A combination using earlier CDF and D0 measurements [32] yields an inclusive $t+s$-channel cross section of $2.76^{+0.58}_{-0.47}$ pb, assuming the top quark mass of 170 GeV.

<table>
<thead>
<tr>
<th></th>
<th>$t$-channel</th>
<th>$s$-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>$1.49^{+0.47}_{-0.42}$</td>
<td>$1.81^{+0.63}_{-0.58}$</td>
</tr>
<tr>
<td>D0</td>
<td>$2.90^{+0.59}_{-0.59}$</td>
<td>$0.98^{+0.62}_{-0.63}$</td>
</tr>
</tbody>
</table>

**Table 1.4:** Single-top quark production cross sections in $t$- and $s$-channels measured by CDF and D0 collaborations of the Tevatron with unit in picobarn.

The measurement of the $t$-channel cross section has also been carried out at the LHC by the ATLAS [33] and CMS [34] experiments using more than 1 fb$^{-1}$ of data collected in 2011. By fitting the distribution of a multivariate discriminant constructed with a neural network, ATLAS extracts the $t$-channel cross section of $83 \pm 4\text{(stat.)}^{+20}_{-19}\text{(syst.)}$ pb. The measurement of CMS combines an analysis exploiting the pseudo-rapidity distribution of the light jet scattered off the top quark with two multivariate analyses and yields the cross section of $67.2 \pm 6.1$ pb. Since the $s$-channel production is relatively small at the LHC, recent measurement performed by ATLAS with 0.7 fb$^{-1}$ data only set the upper limit of 26 pb.

With the $t$-channel cross section measured at both the Tevatron and the LHC, Figure 1.10 compares the theoretical predictions with those experimental measurements.
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1.3.2 The $Wt$-channel

The single top quark can be also produced in association with a real $W$ boson in the so-called $Wt$-channel. The main partonic processes for $t$ and $\bar{t}$ productions are $gb \rightarrow tW^-$ and $g\bar{b} \rightarrow \bar{t}W^+$ respectively, since other CKM-suppressed contributions from $gs$ and $gd$ initial states are negligibly small. The Feynman diagrams representing the leading order partonic processes are shown in Figure 1.11 in the 5-flavor scheme.

Figure 1.10: Experimental measurements of the $t$-channel cross section at the Tevatron and the LHC in the comparison with the Standard Model predictions. Figure taken from [34].

Figure 1.11: Leading order Feynman diagrams for single-top $Wt$-channel production.

A key issue to be tackled when considering the NLO corrections is the separation of final states arising from $Wt$-channel and $t\bar{t}$ intermediate states. One example is illustrated in Figure 1.12. The QCD correction taking into account the process
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$gg \to tW^-$ where one gluon splits into a virtual $b$ and a real $\bar{b}$ (Figure 1.12(a)), can be also processed via an intermediate $t\bar{t}$ state where not only the $t$, but also the $\bar{t}$ is on-shell and decays into $W^-\bar{b}$ (Figure 1.12(b)). When integrating over the phase space, the $t\bar{t}$ contribution has to be subtracted in order to determine the ‘genuine’ $Wt$ cross section.

![Feynman diagrams](image)

**Figure 1.12:** Feynman diagrams corresponding to (a) the $Wt$-channel NLO correction and (b) the intermediate $t\bar{t}$ state.

Several methods were proposed and studied in literature. For example, [35] performed a cut on the invariant mass of the $W^-\bar{b}$ system close to $m_t$ to prevent the $\bar{t}$ from becoming resonant, while [36] subtracted the leading order $t\bar{t}$ contribution by $\sigma_{LO}(gg \to t\bar{t})B(\bar{t} \to W^-\bar{b})$. Using the later subtraction approach, the NLO corrections to the $bg \to tW^-$ (5-flavor scheme) were calculated by [37]. The approximate NNLO cross section with accuracy up to the NNLL calculated recently by [38] is given in Table 1.3. Unlike the $t$- and $s$-channels, the $t$ and $\bar{t}$ production is symmetric in the $Wt$-channel at both the Tevatron and the LHC.

The $Wt$-channel plays no role at the Tevatron, but the observation of it is expected at the LHC as the $Wt$-channel becomes the second largest source of the single top production given the increased gluon luminosity. Searching for the $Wt$-channel signal at the LHC is nevertheless still challenging due to fact that the cross section of it is still relatively small compared to its background processes.

Using the data collected by the ATLAS experiment at the LHC, it is indeed the aim of this thesis to measure the cross section of the single-top $Wt$-channel production at the centre-of-mass collision energy of 7 TeV.

**Event signature**

In the $Wt$-channel, the top quark is produced in association with a $W$ boson. The top quark decays further into a $b$ quark through the weak interaction emitting another $W$ boson. Since a $W$ boson can decay into a lepton-neutrino pair or two quarks, the final state of a $Wt$-channel event depends on the decay of the two $W$ bosons. We will
concentrate our discussion on the so-called “lepton+jets” mode as it is the mode we will be looking at throughout the thesis.

![Diagram](image1.png)

**Figure 1.13:** Two possible topologies of a single top $Wt$ channel event decaying into the lepton+jets mode.

The signal event topology in the lepton+jets mode is shown in Figure 1.13. Here one $W$ decays into a lepton-neutrino pair while the other into two quarks. Together with the $b$ quark decayed from the top quark, this decay mode is characterized by 3 quarks, a lepton and a neutrino. Through the QCD hadronization, quarks are formed into hadrons, each of them decays subsequently into a cluster of particles recognized as a “jet” in the detector. The lepton$^6$ decayed from the massive $W$ boson will be energetic and isolated, while the energetic neutrino will not be undetectable but leaves its signature in terms of missing energy.

**Background processes**

There are various physics processes with the same or similar event signature as the $Wt$-channel signal. In addition, processes not necessary to have the same or similar event signature can also contribute to the background due to the limitation of the detector acceptance or miss-reconstruction. Focusing on the the lepton+jets decay mode, we discuss in the following the processes being part of the background to the $Wt$-channel signal.

**The top-quark pair production** As discussed in Section 1.2.1, top quarks are produced predominantly in $t\bar{t}$ pairs in the hadron collider. At the LHC, the production cross section is about an order of magnitude larger than the signal. Comparing to the leading-order $Wt$-channel production, the $t\bar{t}$ process should be distinguished by an additional $b$-jet from the decay of the second top quark in the event; however, the $b$-jet may not be identified properly making the $t\bar{t}$ events look similar to the signal. On the

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$^6$Concerning the lepton flavors, only the $e$ and the $\mu$ are considered here (and in this thesis) as the $\tau$ lepton has relatively short lifetime and decays further into a $W$ and a $\nu_{\tau}$ resulting a different event signature.
other hand, if one considers the NLO $Wt$-channel production shown in Figure 1.12(a), an extra $b$-jet can be added to the signal event topology making the signal itself more like a $t\bar{t}$ event. Due to these reasons, the $t\bar{t}$ process is rather an irreducible background even though its total cross section is not the largest among other backgrounds.

**The $W + \text{jets}$ production** The $W$ boson can be produced during the hard scattering together with additional quarks or gluons forming multiple jets in the final states. The total cross section of it is approximately $10 \text{ nb}$ per lepton flavor [39], more than 500 times larger than the signal. Given the presence of the $b$-quark in the signal event, the $W + \text{jets}$ events that have similar signature to the signal are those with 1 or 2 $b$-quarks produced together with the $W$ boson. They are referred to as $Wb + \text{jets}$ or $Wbb + \text{jets}$ events, respectively. Example diagrams of them are shown in Figure 1.14. For this reason, the fractions of the $Wb + \text{jets}$ and $Wbb + \text{jets}$ events within the overall $W + \text{jets}$ background are essential to the measurement of the signal cross section. Once the fraction is determined, those events can be further separated, for example, by considering the invariant mass of the $Wb$ system as it will deviate largely from the top quark mass. In contrast, the $Wb$ invariant mass in the signal event would be close to the top quark mass provided that the selected $W$ is decayed from the top quark.

![Example Feynman diagrams of (a) the $Wb$ production with 2 additional jets and (b) the $Wbb$ production with 1 additional jet.](image)

**The QCD multi-jet production** At the LHC, an anomalous amount of QCD events is produced with the cross section in an order of $1 \text{ mb}$. The majority of them is originated from the $2 \rightarrow 2$ QCD process resulting in 2 energetic jets of particles in the event. The initial and final state radiations from the propagating quarks and gluons also add additional jets leading to events with more than 2 jets. With the expectation of an lepton in the signal, the QCD multi-jet events become signal-like when an “extra” lepton appears in the event. Examples such as a jet being misidentified as a “fake” electron or a “real” lepton (electron or muon) being produced in the decay of a heavy-flavor quark are shown in Figure 1.16.
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Figure 1.15: Example Feynman diagrams of the QCD multi-jet events with an extra lepton coming from (a) the decay from a heavy flavor quark or (b) a misidentified jet.

**Single top-quark production in the $t$- and $s$-channels** With the presence of the top quark, single top-quark production in the $t$- and $s$-channels also contributes to the background. Apart from the relatively small cross section comparing to other background processes, it can be distinguished from the signal by topological features. For example, two $b$-jets in the $s$-channel events and a forward jet originating from the $q^0$ in Figure 1.8 in the $t$-channel events.

**Other Standard Model backgrounds** With the leptonic decay of the $W$ and $Z$ bosons, there are two other Standard Model processes contributing to the background, namely the $Z$+jets and di-boson productions. Figure 1.16(a) shows an example diagram of the $Z$+jets event with the $Z$ boson decaying into a pair of leptons. At the LHC, the cross section of $Z$+jets production with the $Z$ boson decaying into two leptons is about 1 nb per lepton flavor. Nevertheless, the $Z$+jets events only become similar to the signal when one of the leptons from the $Z$ decay is not identified. The di-boson production also take part of the background when one of the bosons decays leptonically. Example diagrams corresponding to the productions of $WW$, $WZ$ and $ZZ$ are illustrated in Figure 1.16(b), 1.16(c) and 1.16(d), respectively. The inclusive cross section of di-boson production at the LHC is about 70 pb. The majority of di-boson events can also be suppressed by requiring events to contain multiple jets and an isolated lepton.

1.3.3 Physics beyond the Standard Model

Because of its large mass, the top quark itself has tight connection with theories beyond the Standard Model through the coupling with heavier new particles predicted by the theories. New physics would essentially modify the $Wtb$ vertex of the SM top quark decay and affect the top quark’s decay width. In principle, Equation 1.4 would already serve the purpose of probing new physics. However, it is difficult to measure
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Figure 1.16: Example Feynman diagrams of (a) $Z$+jets and (b)-(d) the di-boson production processes. The dashed-line indicates the lepton not being identified due to imperfections of the detector acceptance or the event reconstruction.

the top quark decay width in the hadron collider since the experimental resolutions are much larger than the width itself [40].

Physics beyond the Standard Model can also be probed by the top quark production through the electroweak interaction, the single-top production, as its cross section is directly proportional to the top quark’s weak coupling. The sensitivity of the single top production to new physics was argued by [41] as the following. If new physics appears at some energy scale $\Lambda$, its effect on the single top production would scale as $(\sqrt{s}/\Lambda)^n$ where $\sqrt{s}$ is the centre-of-mass energy of the reaction and $n$ is either a positive integer or 0, while the effect on the top quark decay would scale as $(m_t/\Lambda)^n$. At high energy colliders such as the Tevatron and LHC, $\sqrt{s}$ can be considerably larger than $m_t$, thus enhancing the relative importance of new physics in single top production.

Testing the Standard Model itself serves as a way to probe physics beyond the Standard Model. For example, the assumptions of the three-quark-generation model and the weak universality in the Standard Model imply that the $|V_{tb}|$ of the CKM matrix should be close to 1. With the cross section directly proportional to $|V_{tb}|^2$, the single top production provides the only direct measurement of $|V_{tb}|$. Certain new physics scenarios, such as the presence of the 4th generation quarks [42], would lead the $|V_{tb}|$ to deviate from the unity.

New physics can be assessed in various forms in the three single top production channels with different sensitivities. Hereafter we will go through the three channels
and discuss the new physics they are most sensitive to.

$t$-channel

In the Standard Model the flavor quantum number of fermions can be changed by charged currents, i.e., through the weak interactions mediated by the exchange of a $W^\pm$ boson. Flavor changing neutral currents (FCNC) processes such as $t \rightarrow q X^0$ where $X^0$ is a charge-neutral boson (photon, $Z$, gluon or $H$) are absent at tree level. FCNC can happen in higher-order loop diagrams with the help of a virtual $W$-boson; however this kind of processes is highly suppressed through the GIM mechanism to the branching ratio of $10^{-10} \sim 10^{-14}$. Several new physics beyond the Standard Model suggest that the FCNC branching ratio can be significant enhanced by 7-10 orders of magnitude [44].

![Feynman diagram](image.png)

**Figure 1.17:** Feynman diagram of the flavor changing neutral currents contribution to the single-top $t$-channel production.

The $t$-channel is sensitive to the FCNC. The corresponding tree-level Feynman diagram is illustrated in Figure 1.17. Since the required $c$ or $u$ parton at the reaction initial state has higher density than the $b$-parton, it would compensate the smaller FCNC coupling. Also the FCNC operators involves a different set of spectator quarks in the reaction, they do not interfere with the SM $t$-channel process; therefore, the presence of the FCNC beyond the SM will be seen as an enhancement of the $t$-channel cross section.

FCNC may also be seen in the $s$-channel through reactions such as $qq \rightarrow Z \rightarrow tc$; however, those new physics signals may be difficult to extract in practice as it requires identification on the $c$ quark in association with the top quark. As the $Wt$-channel requires the $W^\pm$ to be on-shell, it receives no contribution from the FCNC.

$s$-channel

A simple extension of the SM is to postulate the existence of a larger gauge group which somehow reduced to the SM gauge group at low energies. Theories along this line predict additional heavier gauge bosons and some of them will couple with the top quark.
The single-top s-channel would be an ideal place to probe the top quark coupling with heavier gauge bosons. For example, the appearance of $W'$ will contribute to the s-channel production through the process of $qar{q} \rightarrow W' \rightarrow t\bar{b}$ with exchange of a virtual $W'$. The corresponding Feynman diagram is shown in Figure 1.18. Because of the interference with the SM process exchanging a virtual $W$, the net rate of the s-channel production can be increased or decreased. However, if enough energy is available, the $W'$ may be produced close to on-shell resulting as a signature on the resonance spectrum.

Top quark coupling with $W'$ is possible in $t$-channel, but it is suppressed by $1/M_{W'}^2$, as the virtual $W'$ must have a spacelike momentum. In the $Wt$-channel, exotic production such as $gb \rightarrow tW'$ can happen, however, one would expect $W'$ decays dominantly to $bt$ resulting in a quite different final state with two top quarks and one $b$ quark. One should note that such argument applies to the coupling with other heavier gauge bosons such as the charged Higgs bosons.

$Wt$-channel

In the Standard Model, the $Wtb$ coupling is entirely left-handed. New physics beyond the Standard Model may present itself in a different type of the $Wtb$ coupling. It can be investigated by considering the general form of the Lagrangian for the $Wtb$ interaction [45]:

$$\mathcal{L} = -\frac{g_w}{\sqrt{2}} V_{tb} \left[ \bar{b}\gamma_\mu (f_1^L P_L + f_1^R P_R) t W^-_\mu + \bar{b}\gamma_\mu q_\nu \frac{f_2^L P_L + f_2^R P_R}{M_W} t W^-_\mu \right] + h.c. \quad (1.6)$$

where $M_W$ and $q_\nu$ are the mass and the four-momentum of the $W$ boson, respectively. $P_L = (1 - \gamma_5)/2$ and $P_R = (1 + \gamma_5)/2$ are the left-handed and right-handed projection operators, respectively, and $i\sigma_{\mu\nu} = -\frac{1}{2} [\gamma_\mu, \gamma_\nu]$. The Standard Model contribution expressed by Equation 1.5 is a reduction of the general Lagrangian if one sets the form factors $f_1^L = 1$ and $f_1^R = f_2^L = f_2^R = 0$. Anomalous $Wtb$ coupling due to new physics
beyond the Standard Model can be studied by examining the possible deviations of those form factors from their Standard Model settings.

Although the anomalous $Wtb$ coupling should display its effect on the production cross sections of the three single-top production channels, the $Wt$-channel is the purest one to probe it given the fact that the possible contaminations from the FCNC and the coupling with new heavier gauge bosons are negligible as discussed before.

1.4 Summary

Top quark, the heaviest Standard Model particle, was described in this chapter. The large mass makes the top quark one of the interesting particles to be studied at the hadron colliders with high energy. After two decades of its prediction by theory, the top quark was observed at the Tevatron. Intensive studies on its properties have just begun at the LHC where physicists will benefit from a significant amount of the top quarks produced in pairs.

Apart from the top quark pair production, single top quark production through electroweak interaction was also discussed. Searching for single top quark production is of an interest as it serves not only as a test to the Standard Model but also a probe of new physics beyond the Standard Model. Among the three channels of the single top production, only the $t$- and $s$-channels were observed recently at the Tevatron. The $Wt$-channel production is expected at the LHC although the search of it is nevertheless a challenge due to its low cross section overwhelmed by large backgrounds. Motivated by the challenge, we will present in this thesis one of the first cross section measurements on the single top quark production in the $Wt$-channel, using the data of the LHC $p - p$ collisions at $\sqrt{s} = 7$ TeV collected by the ATLAS detector in 2011.