

Chapter 2

Theoretical Background

2.1 The Standard Model

2.1.1 Matter Particles

All known fundamental particles are classified as either quarks, leptons or gauge bosons. The quarks and leptons are spin-1/2 fermions and constitute the building blocks of matter. They are grouped into three generations, where the lightest particles are found in the first generation, and the heaviest in the third generation. Each generation contains a charged lepton, a charge-neutral neutrino, and an up-type and a down-type quark with charges $+2/3$ and $-1/3$, respectively. Quarks carry colour charge and never appear as free particles but in bound states called hadrons. The properties of the quarks and leptons are summarized in Table 2.1. For each particle in this table, there is an anti-particle with exactly the same mass, but opposite quantum numbers, such as electric charge and colour charge.

2.1.2 Particle Interactions

The quarks and leptons interact with each other via the exchange of spin-1 gauge bosons. There are three kinds of gauge bosons corresponding to the three interactions (forces) described in the standard model. The photon is the gauge boson for the electromagnetic interaction, which occurs between particles carrying electric charge. The massive W^+ , W^- and Z^0 bosons mediate the weak force, and massless gluons are the carriers of the strong force acting on particles with colour charge. The standard model also predicts the existence of the Higgs mechanism, which generates the mass for the elementary particles. An overview of all particles and their interactions is illustrated in Fig. 2.1.

Table 2.1 Properties of the matter particles [1]

Generation	Quarks			Leptons		
	Flavour	Charge	Mass	Flavour	Charge	Mass
I	up u	+2/3	1.5–3.3 MeV	electron e	−1	0.511 MeV
	down d	−1/3	3.5–6.0 MeV	e neutrino ν_e	0	<2.2 eV
II	charm c	+2/3	1.27 GeV	muon μ	−1	105.7 MeV
	strange s	−1/3	70–120 MeV	μ neutrino ν_μ	0	<0.17 MeV
III	top t	+2/3	171.2 GeV	tau τ	−1	1.777 GeV
	bottom b	−1/3	4.2 GeV	τ neutrino ν_τ	0	<16 MeV

The masses for the u , d and s quarks are estimates of the “current quark mass” at a 2 GeV scale in the $\overline{\text{MS}}$ scheme, and the masses for the c and b quarks are the “running quark masses” using the same scheme. The top quark mass is from direct observations in data

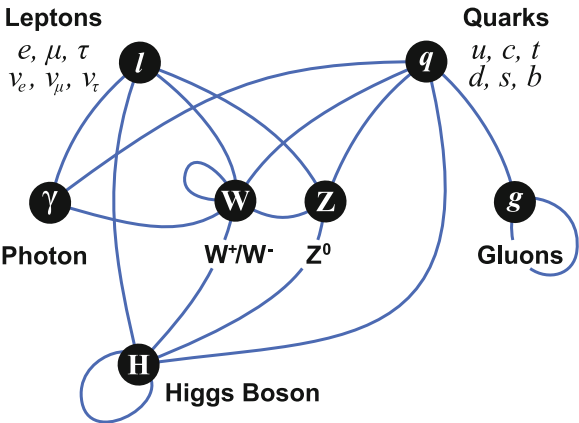


Fig. 2.1 Illustration showing all fundamental particles and interactions described in the standard model. The electromagnetic force is mediated by the photon that couples to all charged particles. The W and Z bosons carry the weak force between left-handed particles, and the gluon is the force carrier of the strong interaction, and couples to particles with colour charge. The Higgs boson, which is part of the standard model but not yet observed, couples to all massive particles

2.1.3 Gauge Theories

The standard model incorporates the gauge theories of the electroweak and strong interactions. A gauge theory is a quantum field theory (QFT) which is invariant under certain symmetry transformations. Massless gauge fields are introduced by demanding the Lagrangian for a gauge theory to be invariant under *gauge transformations*—symmetry transformations which depend on the space–time coordinate. Excitations (quanta) of a gauge field represent spin-1 gauge bosons that carry the force associated with the field.

The electroweak interaction belongs to the $SU(2)_L \times U(1)_Y$ gauge group. L here indicates that the weak force only couples to left-handed particles, and Y

refers to the weak hypercharge. In an unbroken form, the electroweak gauge group requires all of its bosons to be massless. This is not the case in nature since W and Z bosons are known to have large mass. In the standard model, particles acquire mass through the *Higgs mechanism*, which introduces a doublet of complex scalars whose self-interaction breaks the electroweak symmetry. This results in one physical scalar Higgs boson, which is the only elementary particle predicted by the standard model that is not yet observed.

The standard model is the combination of the electroweak and the strong interactions, which forms the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group. The first term in this expression is the gauge group for the strong force, and the subscript C here refers to the colour charge.

2.2 The Top Quark

2.2.1 Discovery

The top quark was predicted in 1977 when the b quark was discovered at Fermilab [2]. The b quark was observed to be a down-type quark, and since the theory requires each quark to have an isospin partner, the top quark was postulated as an up-type quark. It can be produced both via the strong interaction and via the electroweak interaction.

The top quark was discovered in 1995, 18 years after the b quark, by the DØ and CDF Collaborations at Fermilab [3, 4]. It was observed produced in pairs via the strong interaction. The Feynman diagrams for top pair production are shown in Fig. 2.2.

It took another 14 years before electroweak top quark production was discovered. This thesis presents this observation.

2.2.2 Properties

Just like the other up-type quarks, the top quark participates in both strong and electroweak interactions and has spin $1/2$ and charge $+2/3e$. However, it also exhibits several unique properties. It has the largest mass of any elementary particle; its mass is approximately that of a tungsten atom, nearly 40 times larger than the mass of the b quark and 10^4 times heavier than the up and down quarks. The large mass comes with a very short lifetime of about 0.4×10^{-24} s. This is shorter than the hadronization time scale of $\sim 3.0 \times 10^{-24}$ s, which means that the top quark decays as a free particle before undergoing fragmentation, transmitting its properties cleanly to the decay products.

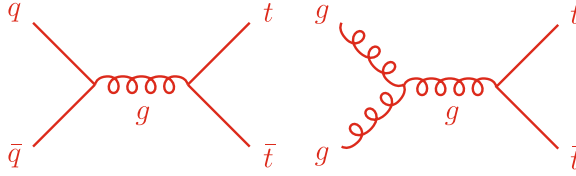


Fig. 2.2 Representative Feynman diagrams for $t\bar{t}$ production. The left diagram shows quark–antiquark annihilation, the right one shows gluon–gluon fusion. Quark–antiquark annihilation is the dominant production channel at the Tevatron (85, 15% for gluon fusion)

2.2.3 Decay

The top quark decays nearly exclusively to a W and a b quark. In the standard model, the branching ratio $\mathcal{B}(t \rightarrow Wb)$ is greater than 0.998. The b quark from the top decay will form a jet, but the W boson has many different decay modes. A top quark decay is therefore categorized by the decay of the W , which either decays to a lepton and a neutrino, or to a quark–antiquark pair. All lepton flavours are kinematically allowed, but the hadronic decay is limited to the first two generations of quarks since $m_W < m_t$. At leading order, a hadronic decay is three times as likely as a leptonic decay since quarks come in three colours, and we get $\mathcal{B}(W \rightarrow q\bar{q}') = 1/3$ and $\mathcal{B}(W \rightarrow \ell\nu) = 1/9$ for a given quark/lepton flavour (except $W \rightarrow tb$ as mentioned above). Higher order corrections slightly alter this symmetry. A summary of the W decay modes is shown in Table 2.2.

2.3 Electroweak Top Quark Production

2.3.1 Introduction and Motivation

Electroweak top quark production is usually referred to as *single top* quark production since only one top quark is produced per event. Top quarks are here produced in charged current interactions via the Wtb vertex, which contributes by the factor

Table 2.2 Experimentally measured branching ratios for the decay of a real W [1]

Decay mode	Branching ratio (%)
$W^+ \rightarrow \ell\nu$	10.80 ± 0.09
$W^+ \rightarrow e\nu$	10.75 ± 0.13
$W^+ \rightarrow \mu\nu$	10.57 ± 0.15
$W^+ \rightarrow \tau\nu$	11.25 ± 0.20
$W^+ \rightarrow \text{hadrons}$	67.60 ± 0.27

In the analysis presented in this thesis, the combined $\mathcal{B}(W \rightarrow \ell\nu)$ is used for each lepton flavour (see Table 5.4.)

$$\frac{-ig_w}{2\sqrt{2}}V_{tb}\gamma^\mu(1-\gamma^5) \quad (2.1)$$

to the matrix element for single top quark production. As a result, the single top quark production cross section is directly proportional to $|V_{tb}|^2$. From a measurement of the cross section, one can hence extract $|V_{tb}|$, without any assumptions on the number of generations in the standard model.

Single top quark production also offers opportunities to probe physics beyond the standard model, such as new exchange particles and flavour changing neutral currents. Further, after isolating single top quark events, it is possible to measure several of the top quark properties, such as the spin polarization. Finally, single top quark processes produce the same final state as the standard model Higgs boson process $WH \rightarrow Wb\bar{b}$ as well as the charged Higgs process $H^+ \rightarrow t\bar{b} \rightarrow Wb\bar{b}$. The background model, and essentially all analysis techniques developed for single top quark analyses, can hence also be used for Higgs searches.

Because of these interesting properties, single top quark production has been extensively studied, see for example Refs. [5–15].

2.3.2 Production Modes

At hadron colliders, there are three single top quark production modes, the s - and t -channel exchanges of a virtual W , and tW production. The next to leading order (NLO) cross sections for these processes at the Tevatron are given in Table 2.3.

t -channel single top quark production is the dominant single top quark production mode at the Tevatron. In this process, a virtual, space-like W boson ($Q_W^2 < 0$, where Q_W is the W four-momentum) interacts with a b quark from the proton sea. This process also has the alias Wg fusion, since the b quark originates from a gluon in the sea splitting into a $b\bar{b}$ pair. The most important Feynman diagrams for t -channel single top quark production are presented in Fig. 2.3. There is a $2 \rightarrow 3$ and a $2 \rightarrow 2$ diagram where the latter is a sub-process of the former where the gluon splitting in the sea has been ignored.

The s -channel single top quark production is, at leading order, the process $q\bar{q}' \rightarrow t\bar{b}$ which is illustrated in Fig. 2.4. In this process, the exchange particle is a time-like W boson with $Q_W^2 > (m_t + m_b)^2$.

Table 2.3 NLO single top quark production cross sections at the Tevatron (1.96 TeV $p\bar{p}$ collider) for $m_t = 170$ GeV [16]

Process	Cross section (pb)
t -channel	2.34 ± 0.14
s -channel	1.12 ± 0.06
tW	0.28 ± 0.06

For comparison, the corresponding NLO $t\bar{t}$ production cross section is $7.91^{+0.61}_{-1.01}$ pb [17]

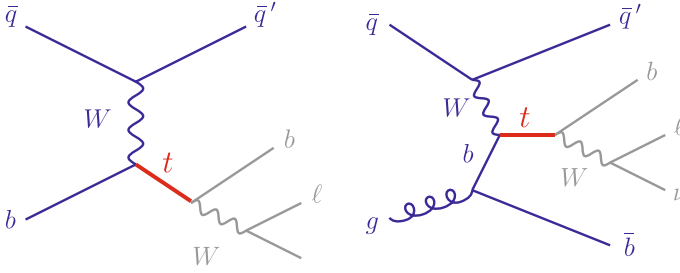
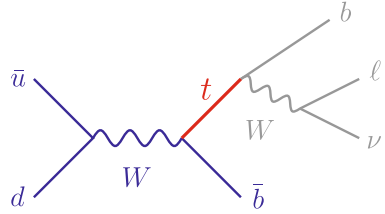


Fig. 2.3 The leading order $2 \rightarrow 2$ (left) and $2 \rightarrow 3$ process (right) Feynman diagrams for t -channel single top quark production. The left diagram is a subset of the right

Fig. 2.4 Leading order s -channel single top quark production



The tW process produces top quark with an on-shell W ($Q_W^2 = m_W^2$). The cross section for this process is very small at the Tevatron, and this production mode is therefore ignored in this analysis.

2.3.3 Measurement of $|V_{tb}|$

The Cabbibo–Kobayashi–Maskawa (CKM) quark mixing matrix describes the relationship between the quark mass eigenstates (d, s, b) and the weak eigenstates (d', s', b') during charge current interactions. Within the standard model with three generations, unitarity of the CKM matrix gives

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1. \quad (2.2)$$

Since $|V_{ub}|$ and $|V_{cb}|$ have been precisely measured, this implies a tight restriction on $|V_{tb}|$ [1]:

$$0.999090 < |V_{tb}| < 0.999177. \quad (2.3)$$

However, if we do not assume three generations, then Eq. 2.2 becomes

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 + \dots = 1, \quad (2.4)$$

and the constraints on $|V_{tb}|$ change to [15]:

$$0.06 < |V_{tb}| < 0.9994. \quad (2.5)$$

As previously mentioned, the single top quark production cross section is proportional to $|V_{tb}|^2$. From a measurement of the single top quark production cross section, we can therefore extract a measurement of $|V_{tb}|$. A measurement that differs significantly from the range specified in Eq. 2.3 would be clear evidence for physics beyond the standard model, and could possibly indicate the existence of a fourth generation of quarks.

The first direct measurement of $|V_{tb}|$ was presented in 2006 by the DØ Collaboration together with evidence for single top quark production [5, 6]. This analysis conducts a refined measurement using a larger dataset, see Sect. 7.5.

2.3.4 Single Top Kinematics

Figure 2.5 shows various kinematic distributions for the final state particles produced in s - and t -channel single top quark production (see Figs. 2.3, 2.4). These distributions are from the Monte Carlo samples used to simulate single top in this analysis. The modeling of these samples is described in Sect. 5.4.2

There are several characteristic kinematic features of single top quark production that can be seen in Fig. 2.5. The b quark emitted from the top quark decay tends to be central and has large transverse momentum. For the decay products of the W boson, we see that the lepton has a softer p_T spectrum than that of the neutrino. This occurs because the preferred direction of the lepton is anti-aligned with the top quark direction due to the V–A nature of the weak force, as further discussed in Sect. 2.3.5. The b quark produced in association with the top quark in t -channel single top production tends to have high rapidity and low momentum and is often not reconstructed in the analysis. The light quark produced in the t -channel has reasonably large p_T , but its most distinguishing feature is the asymmetric $Q(\ell) \times \eta$ distribution, where $Q(\ell)$ is the charge of the lepton in the event. This asymmetry arises since the final state light quark produced during single t ($\bar{t}$) production most often is a d ($\bar{d}$) quark that moves in the same direction as the proton (antiproton) [15]. The light quark η will hence tend to have the same sign as the charge of the lepton from the top decay.

2.3.5 Polarization

As earlier discussed (Sect. 2.2.2), top quarks decay before they hadronize, transmitting their properties cleanly to the W boson and the b quark produced in the decay. In the standard model, the Wtb interaction is entirely left-handed, which means that single top quark production is a source of highly polarized top quarks [9].

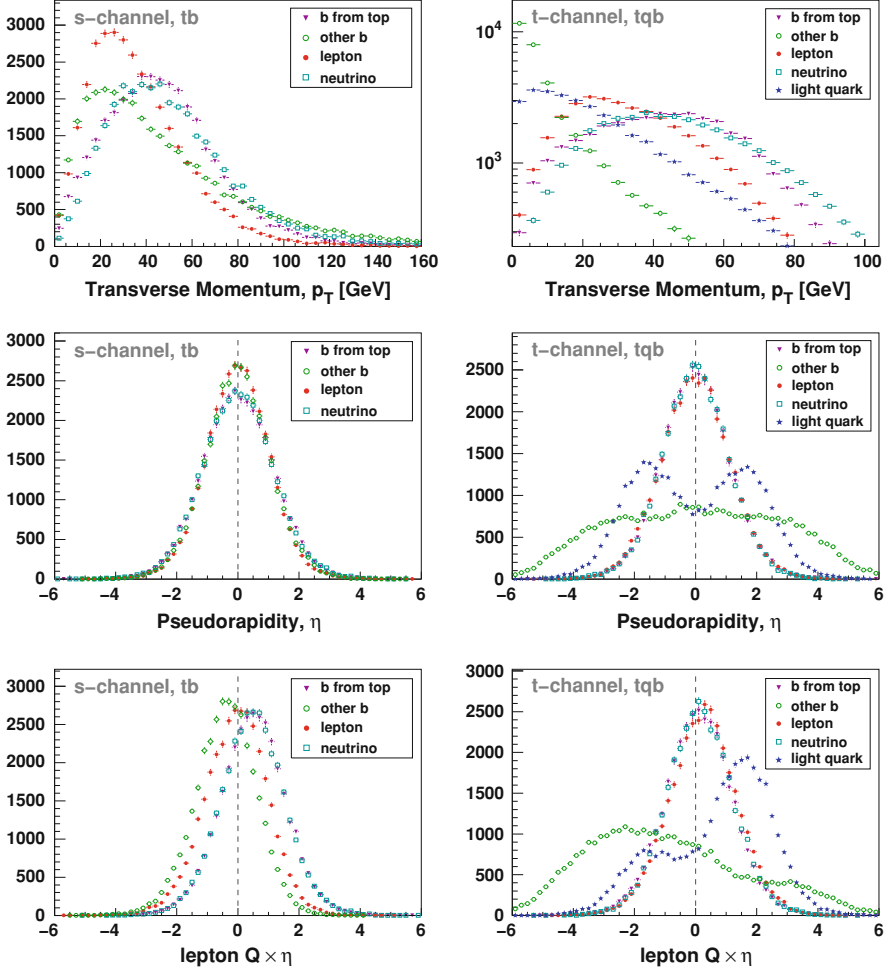


Fig. 2.5 Parton-level kinematic distributions for single top s -channel (left) and t -channel (right) from the single top Monte Carlo samples generated as described in Sect. 5.4.2. The p_T spectrum for each final state particle is shown in the top row, the corresponding η and $Q(\ell) \times \eta$ spectra are shown in the middle and bottom rows, respectively. These distributions were generated after parton showering was applied

The polarization of the top quarks becomes evident in the angular correlations between the decay products (see Fig. 2.6). The lepton is preferably emitted in the same direction as the top quark spin. The distribution of the angle θ_ℓ between the lepton momentum in the top rest frame, and the top polarization vector is given by [9, 15]:

$$F(\theta_\ell) = \frac{1}{2}(1 + \cos \theta_\ell). \quad (2.6)$$

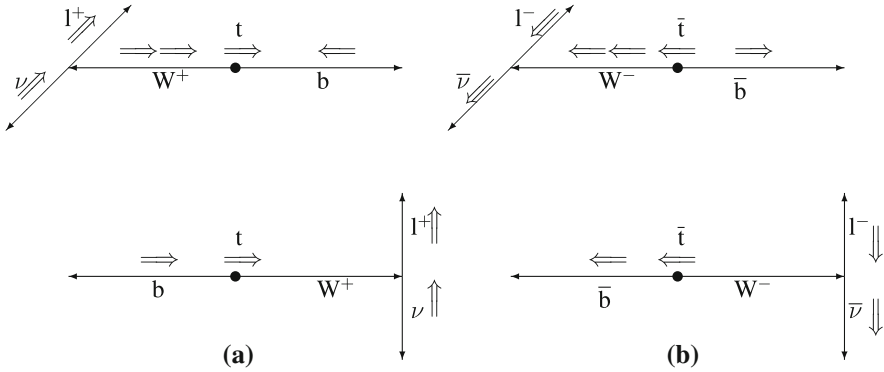


Fig. 2.6 Illustrations of spin and angular correlations in a top decay. *Double arrows* show the preferred direction of the spin and single lines represent the direction of the momentum in the rest frame of the parent particle. The top and anti-top quarks move to the left in all cases, and the preferred spin direction is against (towards) the direction of motion for the top (anti-top) since it is a left-handed (right-handed) particle. The two *upper diagrams* show a top (a) and an anti-top (b) decaying to a transversely polarized W , and the two lower diagrams show the corresponding decays to longitudinally polarized W bosons. In all cases, the charged lepton ℓ^+ (ℓ^-) tends to have its spin aligned with the spin of the top t ($\bar{t}$), and travel against the direction of the top t ($\bar{t}$). This results in a softened lepton momentum distribution as can be seen in Fig. 2.5. (Figure courtesy of [9])

In this analysis, several of the features introduced by top polarization are used to help identify single top quark events, see Sect. 7.1.2.

2.3.6 New Physics

Measuring the single top quark production cross section, and the different angular distributions is interesting as a test of the standard model, but also as a probe for several new physics scenarios beyond the standard model [15].

New physics can affect the single top quark production cross sections for the production modes (tb , tqb and tW) differently. The s -channel (tb) is most sensitive to new, heavy charged bosons. For instance the presence of a heavy W' boson, or a charged Higgs boson $H^\pm$, would increase the measured s -channel single top quark production cross section. The t -channel single top quark production would similarly be enhanced by flavour-changing neutral currents (FCNC). In the standard model, FCNC interactions are forbidden. Representative Feynman diagrams for single top production via an s -channel exchange of a heavy boson and a t -channel FCNC process are shown in Fig. 2.7.

Finally, physics beyond the standard model can alter the $V-A$ structure of the Wtb coupling. This would affect the top polarization, and hence also angular distributions such as $F(\theta_\ell)$ given in Eq. 2.6.

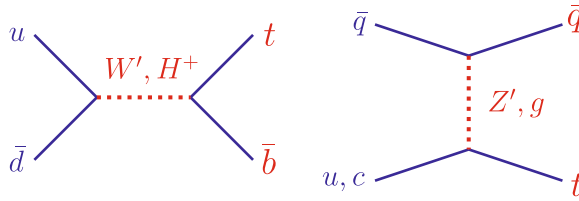


Fig. 2.7 *Left* representative Feynman diagram for anomalous single top quark production via the s -channel exchange of a heavy W' or charged Higgs boson. *Right* Diagram for flavour changing neutral current single top quark production via the t -channel

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