

Chapter 2

The Top Quark in the Context of the Standard Model

2.1 Introduction

The analyses presented in this thesis deal with measurements of the production of top quark pairs at the Large Hadron Collider, as predicted in the framework of the Standard Model of Particle Physics. The first part of this chapter will focus on the theoretical framework in general, while the second part will describe the production and properties of top quarks in more detail and give an overview of the current experimental knowledge of top quark production.

The Standard Model currently provides the best predictions and explanations for the behavior of elementary particles and their properties are measured to great precision in many experiments. No significant deviations from the theoretical predictions are observed so far. However, the Standard Model is limited to an energy up to the TeV-range and has several shortcomings to act as a complete *theory of everything*: It can only explain the visible matter, which makes up only 5 % of the matter in the universe,¹ it does not include gravity and cannot solve the hierarchy problem, there is no further unification of the forces, the missing Higgs boson is still not found, and more. Since the LHC now gives access to a new energy domain, where the Standard Model is expected to unveil its problems, new particles indicating the nature of an underlying theory with the Standard Model as low energy approximation are expected to be observed. Several theories are formulated to solve one or several of the problems, predicting different types of new particles and interactions to be observed at the LHC. The most prominent theories include supersymmetry, extra-dimensions and technicolor models.

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¹ While 23 % are dark matter and the remaining 72 % dark energy.

Table 2.1 Leptons and their properties in the standard model [1]

Particle	Generation	Charge (e)	Mass	Interactions
$e^\pm$	1	± 1	511 keV	Electromagnetic, weak
ν_e	1	0	< 2 eV	Weak
$\mu^\pm$	2	± 1	105.7 MeV	Electromagnetic, weak
ν_μ	2	0	< 2 eV	Weak
$\tau^\pm$	3	± 1	1.78 GeV	Electromagnetic, weak
ν_τ	3	0	< 2 eV	Weak

2.2 The Standard Model of Particle Physics

The Standard Model of Particle Physics, in the remainder referred to as *Standard Model* or SM, is currently the most precise theoretical framework to describe the world of elementary particles. Quantum Mechanics and Special Relativity are combined into a *Quantum Field Theory* to predict interactions and properties of the elementary particles. The Standard Model is based on the idea of combining local gauge symmetries, and leads to conservation laws according to the Noether Theorem. In such a local gauge symmetry, the field behaves invariant under a local gauge transformation $U(x)$,

$$\psi'(x) = U(x)\psi(x) = e^{i\alpha(x)}\psi(x), \quad (2.1)$$

where $\psi(x)$ and $\psi'(x)$ are wave functions of the field satisfying the above equation.

The Standard Model combines the gauge group of a unification of electromagnetism (Quantum Electrodynamics or QED) and weak interactions with the one of Quantum Chromodynamics (QCD), the theory of strong interactions. The fourth fundamental force, gravity, is not included in the Standard Model, limiting its validity to energy scales at which gravity appears small compared to the other three interactions.

The theory predicts the elementary matter particles, six leptons and six quarks with their anti-particle partners, and the mediating gauge bosons for electroweak and strong interactions. In addition, the Standard Model includes a mass-generating mechanism: the Higgs field and its associated boson, the Higgs boson. While all other particles of the Standard Model are observed and well-measured, the Higgs boson remains yet undetected, although measurements at the LHC are continuously limiting the possible mass range for a SM Higgs boson and will shed light on its existence or non-existence in the near future.

The matter particles in the Standard Model, always expressed as fermion fields,² can be grouped into leptons, shown in Table 2.1 and quarks, shown in Table 2.2, and occur in three generations or families with increasing masses. Each of the elementary matter particles has its own anti-particle with opposite quantum numbers, like charges, but the same mass.

² i.e. spin 1/2 particles.

Table 2.2 Quarks and their properties in the standard model [1]

Particle	Generation	Charge (e)	Mass	Interactions
u	1	2/3	1.7–3.3 MeV	Strong, electromagnetic, weak
d	1	−1/3	4.1–5.8 MeV	Strong, electromagnetic, weak
c	2	2/3	1.27 GeV	Strong, electromagnetic, weak
s	2	−1/3	101 MeV	Strong, electromagnetic, weak
t	3	2/3	173.2 GeV	Strong, electromagnetic, weak
b	3	−1/3	4.19 GeV	Strong, electromagnetic, weak

Quark masses are given in the $\overline{MS}$ scheme, except for the top quark mass, where the measured world average is quoted [2]

Table 2.3 Gauge bosons of the standard model and their associated interactions, charges and masses [1]

Gauge Boson	Interaction	Charge (e)	Isospin	Color	Mass
γ	Electromagnetic	0	0	–	$<6 \times 10^{-18}$ eV
$W^\pm$	Weak	± 1	0	–	80.399 ± 0.023 GeV
Z^0	Weak	0	1	–	91.1876 ± 0.0021 GeV
Gluon	Strong	0	0	8 combinations	0

The gauge bosons, particles with spin 1, act as mediators of the interactions between the matter particles and are associated to the different interactions as listed in Table 2.3.

2.2.1 Electroweak Interactions and the Higgs Mechanism

Proposed by Glashow [3], Salam [4] and Weinberg [5] in the 1960s, the theory of electroweak interactions unifies Quantum Electrodynamics with the theory of weak interactions. It combines the symmetry groups $SU(2)$ and $U(1)$ into a $SU(2) \otimes U(1)$ symmetry group. The Pauli-matrices, in the form of the weak isospin T , with $T_i = \frac{\tau_i}{2}$ (where $i = 1, 2, 3$), act as generators of the $SU(2)$ and the corresponding massless gauge fields W_μ^i . The Abelian $U(1)$ group is generated by the hypercharge³

$$Y = 2(Q - T_3)$$

and contains one massless gauge field B_μ .

Since left-handed⁴ fermions occur as doublets with isospin $T_3 \neq 0$, while right-handed fermions only appear as singlets with $T_3 = 0$, only the former transform

³ Where Q denotes the electric charge and T_3 the third component of the weak isospin.

⁴ A massless fermion is identified as left-handed if the direction of motion and spin are opposite to each other, and as right-handed otherwise. For massive leptons the handedness is defined as the chirality, describing the behavior under right- and left-handed transformations.

under the $SU(2)$ symmetry. On the other hand, fermions of both helicity states transform under the $U(1)$ symmetry. Therefore, the interactions have to be described with separate Lagrangians and their covariant derivatives for both types of fermions:

$$D^\mu = \partial^\mu + ig \frac{\tau_i}{2} W_\mu^i + i \frac{g'}{2} Y B^\mu \quad (2.2)$$

for left-handed fermions and

$$D^\mu = \partial^\mu + i \frac{g'}{2} Y B^\mu \quad (2.3)$$

for right-handed fermions. The variables g and g' describe the coupling constants of the $SU(2)$ and $U(1)$, respectively.

From that, the gauge bosons can be derived as linear combinations of the gauge fields, where the *Weinberg-angle* θ_W ⁵ describes the mixing between the $SU(2)$ and $U(1)$. It is defined as

$$\sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}} \quad (2.4)$$

and measured [1] to be

$$\sin^2 \theta_W = 0.23116 \pm 0.00013. \quad (2.5)$$

The Weinberg-angle also relates the electromagnetic charge to the coupling constants of the $U(1)$ and $SU(2)$

$$e = g \sin \theta_W = g' \cos \theta_W. \quad (2.6)$$

The neutral gauge bosons, mediating the neutral currents of electromagnetism and weak interactions, can then be written as

$$\gamma = A_\mu = W_\mu^3 \sin \theta_W + B_\mu \cos \theta_W \quad (2.7)$$

and

$$Z^0 = Z_\mu = W_\mu^3 \cos \theta_W - B_\mu \sin \theta_W. \quad (2.8)$$

Similarly, the charged bosons are expressed as

$$W^\pm = W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp i W_\mu^2), \quad (2.9)$$

associated to the $SU(2)$ symmetry of the combined symmetry.

⁵ Also called the *weak mixing angle*.

In the model of electroweak interactions itself the gauge bosons γ , Z^0 and $W^\pm$ are massless itself, since they are linear combinations of massless gauge fields. The Lagrangian of this model can be written as

$$\begin{aligned} \mathcal{L}_{EW} = & \psi_L^\dagger \gamma^\mu (i\partial_\mu - g \frac{\tau_i}{2} W_\mu^i - \frac{g'}{2} Y B_\mu) \psi_L + \psi_R^\dagger \gamma^\mu (i\partial_\mu - \frac{g'}{2} Y B_\mu) \psi_R \\ & - \frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}, \end{aligned} \quad (2.10)$$

with the first two terms describing the interactions between particles, mediated by the gauge bosons, and the second two terms the interactions between the gauge fields themselves. The wave function ψ_L describes the behavior of a left-handed fermion doubled and the wave function ψ_R the behavior of a right-handed fermion singlet. The interactions between the gauge fields are expressed through

$$W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - ig\epsilon^{ijk} W_\mu^j W_\nu^k \quad (2.11)$$

and

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu. \quad (2.12)$$

While experimental verification for the existence of the gauge bosons exists, the $W^\pm$ and Z^0 bosons are found to have non-zero masses of the order of 100 GeV. This cannot be explained with the electroweak model alone, and the most popular and straight-forward extension is the addition of the Higgs field as an additional field [6–9].

The new field should act invariantly under transformations of the $SU(2)$ of the electroweak theory and is constructed with hypercharge $Y = 1$ and weak isospin $T_3 = \frac{1}{2}$ as a doublet of two complex scalar fields, described as

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (2.13)$$

This proposal adds an additional term to the Lagrangian of the Standard Model of the form

$$\mathcal{L}_{Higgs} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2. \quad (2.14)$$

The terms $\mu^2 \phi^\dagger \phi$ and $\lambda (\phi^\dagger \phi)^2$ resemble a potential $V(\phi^\dagger \phi)$, defined by the choice of the parameters μ and λ . If the parameters are chosen to be $\mu^2 < 0$ and $\lambda > 0$ the vacuum expectation value v of the potential is given by

$$v = \pm \sqrt{\frac{-\mu}{\lambda}}, \quad (2.15)$$

and one possible configuration is shown in Fig. 2.1. A non-zero vacuum expectation value is equivalent to spontaneous symmetry breaking around the minimum, which

creates a real Goldstone boson, the Higgs boson, with a mass of $m_H = \sqrt{2}\mu$ and spin 0. In this extended version of the electroweak theory the gauge boson masses are expressed in terms of the vacuum expectation value with

$$m_W = \frac{1}{2}g v, \quad (2.16)$$

$$m_Z = \frac{1}{2}v\sqrt{g^2 + g'^2} \quad (2.17)$$

and

$$m_\gamma = 0. \quad (2.18)$$

These values are confirmed by experimental measurements, but the value of the parameter μ and thus the Higgs mass remain unknown. However, experimental tests at the LEP, Tevatron and, most recently, the LHC experiments⁶ limit the allowed mass range for the Higgs boson in the SM significantly to $115.5 \text{ GeV} < m_H < 127 \text{ GeV}$ ⁷ [10–13].

The Higgs mechanism does not only generate the masses of the mediating gauge bosons, but also the masses of the fermions, which couple to the Higgs field with the *Yukawa coupling* G_f and add another term $\mathcal{L}$ to the SM Lagrangian. The coupling constant G_f is then another parameter of the Standard Model, leading to fermion masses with

$$m_f = \frac{1}{\sqrt{2}}G_f v. \quad (2.19)$$

Since the top quark is the elementary matter particle with the highest mass, it consequently has the largest coupling to the Higgs field, $G_f \approx 1$. Precise knowledge of its mass, together with precise measurements of the W boson mass and many quantities in the electroweak sector, led to the best indirect predictions of the Higgs boson mass in a global electroweak fit.

Electroweak theory also describes the mixing of the weak eigenstates of quarks in the Cabibbo-Kobayashi-Maskawa-matrix (CKM matrix) [14, 15]. Flavor changing currents between quarks are only possible in weak interactions mediated by charge carrying W bosons. The weak eigenstates q' of the down-type quarks (charge $-\frac{1}{3}$) connect to their mass eigenstates with the unitary, diagonalizable CKM matrix V_{CKM} with

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (2.20)$$

The quark mixing parameters are experimentally well tested and constrained from global fits to many measurements in the electroweak sector of the SM but only valid

⁶ ATLAS and CMS.

⁷ At 95 % C.L.

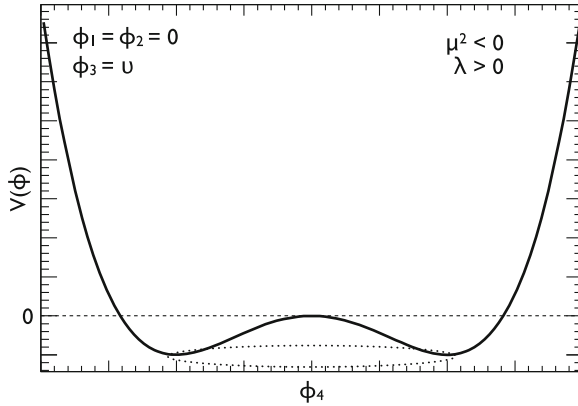


Fig. 2.1 Axially symmetric Higgs potential $V(\phi)$ for the case $\phi_1 = \phi_2 = 0$ and $\phi_3 = v$, in the configuration $\mu^2 < 0, \lambda > 0$

under the above assumptions of three generations [1]:

$$V_{CKM} = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}. \quad (2.21)$$

2.2.2 Quantum Chromodynamics

Developed in the 1960s and early 1970s, Quantum Chromodynamics, or QCD, describes the world of strong interactions between quarks with a non-Abelian local gauge symmetry group $SU(3)$. The quantum number of the strong interaction is called *color* and occurs in three types, *red*, *green*, *blue*, and the respective anti-colors. The mediating gauge bosons are called *gluons* and are realized as an octet of linear combinations of the three color charges.⁸ Only colorless bound states are invariant under transformations of the $SU(3)$, which means that bound states of quarks can only occur as *mesons* in the $|q\bar{q}\rangle$ configuration and as *baryons* in either the $|qqq\rangle$ or $|\bar{q}\bar{q}\bar{q}\rangle$ configuration, with all color charges involved. Since bound states of quarks are experimentally observed, this additional part of the Standard Model is necessary. In a model based solely on the electroweak theory bound states of quarks could violate Pauli's principle, saying that fermions have to differ in at least one quantum number in a bound state system.

Another important feature of QCD is what is called *confinement*: Quarks, which always carry a single color charge, cannot appear as free particles, i.e. outside of

⁸ And a ninth combination as a color singlet, which is not realized in nature.

bound states. As a consequence of this, when trying to separate quarks from one another it becomes energetically preferable to create another pair of quarks with opposite color charge from the vacuum, which then builds new bound states with the two initial quarks. When quarks are generated in high energy particle collisions they transform into *jets* of hadrons, and their decay products, due to this. The only exception is the top quark, which decays into a lighter quark and an additional W boson, before bound states can be formed.

The generators of the $SU(3)$ symmetry group are the eight three-dimensional matrices, with $a = 1, \dots, 8$

$$T_a = \frac{1}{2}\lambda_a, \quad (2.22)$$

expressed in terms of the Gell-Mann matrices λ_a , analogous to the Pauli-matrices generating the $SU(2)$ of weak interactions. With these, the covariant derivative is written as

$$D_\mu = \partial_\mu + ig_s T_a G_\mu^a \quad (2.23)$$

with the gluon fields G_μ^a and the coupling constant g_s . This leads to the Lagrangian of Quantum Chromodynamics with the quark field ψ_q

$$\mathcal{L}_{QCD} = \bar{\psi}_q (i\gamma^\mu \partial_\mu - m)\psi_q - g_s \bar{\psi}_q \gamma^\mu T_a \psi_q G_\mu^a - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}. \quad (2.24)$$

The field strength tensors $G_{\mu\nu}^a$ include a term describing the self-interaction between the gauge bosons, since the gluons carry color charge⁹ and couple to the gauge field itself:

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f_{abc} G_\mu^b G_\nu^c. \quad (2.25)$$

The structure constant f_{abc} describes the relation between the generators of the $SU(3)$ via

$$[T_a, T_b] = if_{abc} T_c, \quad (2.26)$$

while the coupling constant g_s can be related to α_s as

$$\alpha_s = \frac{g_s^2}{4\pi}. \quad (2.27)$$

However, the coupling constant (or α_s) is not a constant but has to be defined in an energy-dependent way to account for divergences occurring from additional internal loops when trying to determine the color charge of a quark. Therefore, α_s has to be expressed as a function of an arbitrary energy scale μ^2 . In the context of the Standard Model, a common scale $\Lambda_{QCD} \approx 200 \text{ MeV}$ is defined which allows to evaluate the coupling constant at an energy scale $Q > \Lambda_{QCD}$ with the formula

⁹ Unlike their massless equivalent in electroweak theory, the charge neutral photon γ .

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f) \log \frac{Q^2}{\Lambda_{QCD}^2}} \quad (2.28)$$

in leading order. The parameter n_f describes the number of active quark types, denoted as f for flavor, i.e. $n_f = 6$ if $Q^2 \geq m_q^2$ is fulfilled for all six quarks of the Standard Model. For this configuration the theory of strong interactions in the SM is *asymptotically free*, meaning that quarks can be considered as *free* at small scales or high energies, since the value for $\alpha_s(Q^2)$ decreases for higher energies [16–18].

2.3 Top Quark Physics

As can be seen in Table 2.2, the top quark is the heaviest of the quarks, significantly heavier than the other quark in its generation, the bottom quark. Once the bottom quark was experimentally discovered in 1977, the existence of a charge $\frac{2}{3}$ -quark in the third quark generation was well expected but could only be observed with the collision energies reached at the Tevatron collider. The top quark was the last quark discovered by both the CDF and DØ collaborations in 1995 [19, 20].

The top quark is special not only due to its large mass, but also due to its short lifetime. This means a *free* top quark produced in a collision decays before it hadronizes, i.e. there are no bound state hadrons made of top quarks. This allows to experimentally test the properties of the bare top quark itself through its decay products without diluting information in the hadronization process. As top quark properties are precisely predicted by the Standard Model, top quark physics provides a sensitive probe of the validity of the Standard Model and a tool to indirectly learn about the Higgs boson and to potentially discover physics beyond the Standard Model. Studying top quark physics is only possible in the data taken by the CDF and DØ experiments at the Tevatron accelerator and by the experiments at the LHC, which can be considered as a ‘top quark factory’ due to the high rate of top quark production. Theoretical predictions and an overview of recent experimental tests especially for top quark pair production, the topic of this thesis, are described in the remainder of this section.

2.3.1 Top Quark Production

At $p\bar{p}$ or pp colliders providing sufficient collision energies to create such particles of high mass, top quarks can be produced in pairs via the strong interaction and as single top quarks in electroweak processes. The most probable production mechanism is the simultaneous production of a top quark and an antitop quark. The electroweak production of a single top quark together with a bottom quark or a W boson is less likely. The production cross section for top quarks, both in pairs and as single quarks,

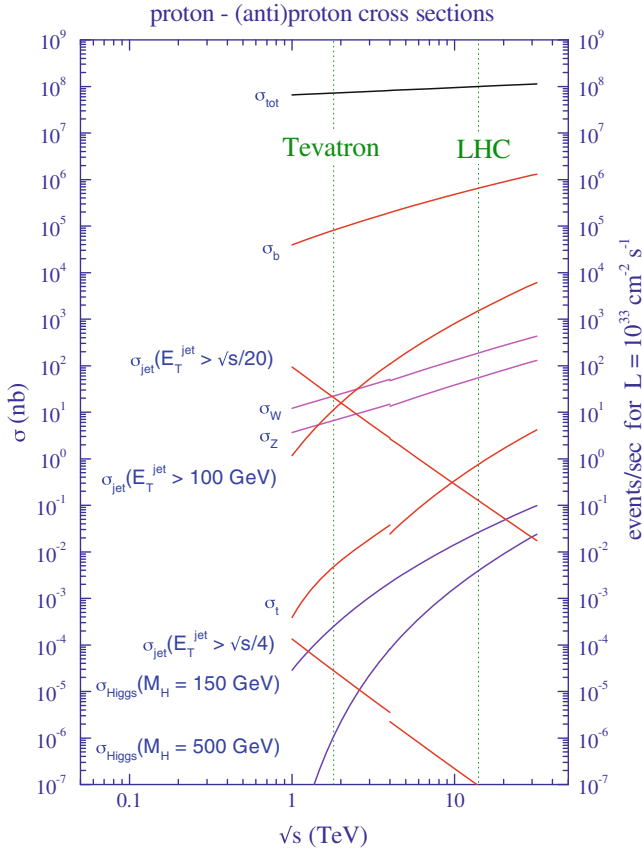


Fig. 2.2 Cross sections of important physics processes at center-of-mass energies reached at the Tevatron and the LHC [21]. The vertical lines indicate the center-of-mass energy at the Tevatron during its RunII and the design centerof- mass energy at the LHC of $\sqrt{s} = 14$ TeV, which is currently operating at $\sqrt{s} = 7$ TeV. The top quark pair production cross section is denoted as σ_t showing the production rate in $p\bar{p}$ collisions at lower energies, and in pp collisions at higher energies

is strongly dependent on the collision energy provided by the accelerator, as shown in Fig. 2.2, and the LHC experiments will acquire a large data set of events with top quarks. Studying these will open up a new field of precision measurements of the Standard Model, as W and Z physics was at the Tevatron and LEP experiments and the processes involving top quarks have to be well understood before exploring less likely processes, such as Higgs physics or searches for new physics in similar final states.

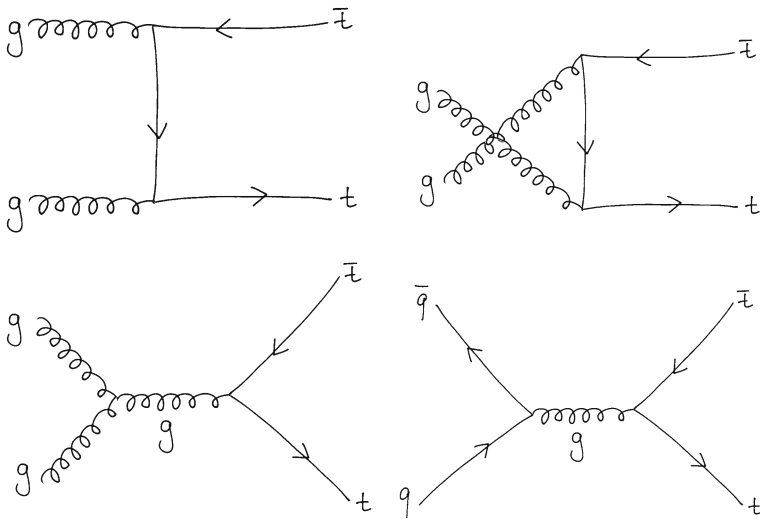


Fig. 2.3 Leading-order production mechanisms for top quark pairs at a pp -collider. At $\sqrt{s} = 7$ TeV the gluon fusion dominates over $q\bar{q}$ annihilation with a ratio of approximately 80:20

2.3.1.1 Top Quark Pair Production

Pairs of a top quark and an antitop quark can be produced in two ways, both shown in Fig. 2.3: gluon fusion and $q\bar{q}$ annihilation. While at the Tevatron collider, in $p\bar{p}$ collisions, $q\bar{q}$ annihilation was the dominating process, the ratio between the contributions of the two production mechanisms inverts at the LHC. This is due to two reasons: the higher center-of-mass energy and the fact, that proton-proton beams collide at the LHC. First of all, $q\bar{q}$ annihilation is disfavored in general at a pp collider compared to a $p\bar{p}$ collider. The antiquark has to be a sea quark in pp collisions, while in $p\bar{p}$ collisions it can be one of the valence quarks of the antiproton, which is more likely to occur at any center-of-mass energy. In addition, at the Tevatron the pair of top quarks is produced right at the threshold of $2m_t$, i.e. the partons participating in the collision have to carry a high fraction x of the proton's momentum. As seen in Fig. 2.4 for the CTEQ66 PDF set [22] used in the presented analyses, at high values of x the up and down valence quarks from the proton¹⁰ dominate, making $q\bar{q}$ annihilation more likely than gluon fusion at the Tevatron with $\sqrt{s} = 1.96$ TeV. At the higher center-of-mass energy of $\sqrt{s} = 7$ TeV partons with small fractions x are already able to produce top quark pairs. Since gluons dominate the parton distribution function of the proton up to high x , gluon fusion becomes the dominating process, even further by the non-existence of valence antiquarks in the LHC's pp collisions.

While no complete calculation of the top quark pair production cross section higher than next-to-leading order (NLO) exists, several different theoretical cal-

¹⁰ Or anti-up and anti-down valence quarks from the antiproton.

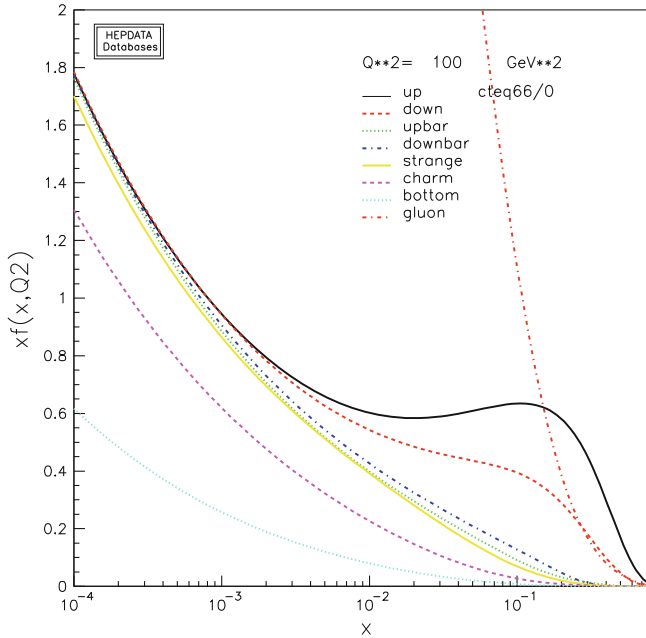


Fig. 2.4 Parton distribution function for protons in the CTEQ66 PDF set [22] at $Q^2 = 100 \text{ GeV}$ [23]

culations of the total top quark pair production cross section at the precision of approximate next-to-next-to-leading order (NNLO) are available. They use different techniques for the higher order approximations and will be briefly summarized here. The top quark pair production cross section, often denoted as $\sigma_{t\bar{t}}$, is dependent on the top quark mass and evaluated for values of m_t close to the world average top mass of $m_t = 173.2 \text{ GeV}$, the value depending on the exact calculations. An overview of the current available NNLO predictions, as described in the following, is shown in Fig. 2.5.

Langenfeld, Moch, Uwer [24, 25]

The calculations considered as theoretical reference for the measurements presented in this work are performed at approximate NNLO by including several different terms, such as next-to-next-to-leading-logarithm (NNLL) enhancements at the threshold, corrections from Coulomb terms in two-loops and scale dependent terms at NNLO. The factorization and renormalization scales can be varied independently. The calculations are provided as a function of the top quark mass. The Hathor framework [26] allows to access the parametrizations and obtain the predicted cross sections for different mass points or center-of-mass energies. For a top quark mass of

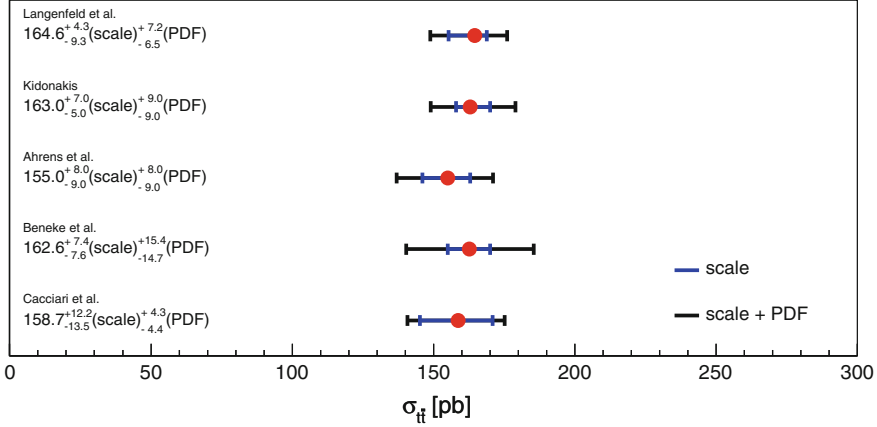


Fig. 2.5 Different approximate NNLO predictions for top quark pair production at $\sqrt{s} = 7$ TeV in pp collisions, as described in the text

$m_t = 172.5$ GeV,¹¹ renormalization and factorization scales of $\mu = m_t$ and the CTEQ66 PDF set, which is used within the context of the presented analyses,¹² a top quark pair production cross section of

$$\sigma_{t\bar{t}} = 164.6^{+4.3}_{-9.3}(\text{scale})^{+7.2}_{-6.5}(\text{PDF}) \text{ pb} \quad (2.29)$$

is predicted. The scale uncertainties are derived by varying the renormalization and factorization scale by factors of 2 and 0.5, while the PDF uncertainties are obtained using the error set for the used PDF set.

Kidonakis [28]

Kidonakis applies two-loop soft anomalous dimension matrices for the resummation of soft-gluon corrections at NNLL. Renormalization and factorization scales are both set to $\mu = m_t$ in the calculations and the PDF set of MSTW2008NNLO [29] is used. At a top mass of $m_t = 173$ GeV, including uncertainties from scale variations with $\frac{1}{2} \leq \mu/m_t \leq 2$ and the PDF error set, the top pair production cross section in pp collisions is calculated to be

$$\sigma_{t\bar{t}} = 163^{+7}_{-5}(\text{scale})^{+9}_{-9}(\text{PDF}) \text{ pb}. \quad (2.30)$$

¹¹ $m_t = 172.5$ GeV is assumed for the Monte Carlo generated samples in the experimental analyses presented and hence the cross section is calculated accordingly.

¹² A similar calculation using the MSTW2008NNLO PDF set, which is better comparable to the other predictions, yields $\sigma_{t\bar{t}} = 165.8^{+4.4}_{-7.0}(\text{scale}) \pm 9.1(\text{PDF}) \text{ pb}$ [27].

Ahrens et al. [30]

The calculations of Ahrens et al. are also based on NNLL resummations and use a combination of two approaches. One is based on an integration over the top quark pair invariant mass distribution, while the other one uses kinematic distributions of a single particle. Techniques from soft-collinear effective field theory are used in a resummation of threshold logarithms in NNLL, which become important when $m_{t\bar{t}}$ is close to the partonic center-of-mass energy $\sqrt{\hat{s}}$, i.e. the top quark pairs are produced at rest. Approximate NNLO results are then calculated for a fixed order in perturbation theory and matched to the available exact NLO calculations at the threshold. The total cross section is derived by integrating over the distribution of choice in both approaches and quoted as the average of the two, while the scale uncertainties take into account both scale variations and also differences in kinematic distributions. This approach yields

$$\sigma_{t\bar{t}} = 155_{-9}^{+8}(\text{scale})_{-9}^{+8}(\text{PDF})\text{pb}, \quad (2.31)$$

using the MSTW2008NNLO PDF set, assuming a top quark pole mass of $m_t = 173.1$ GeV and setting renormalization and factorization scales to $\mu = m_t$.

Beneke et al. [31]

This calculation performs a resummation in NNLL accuracy, but includes terms from Coulomb enhancement, the exchange of virtual Coulomb gluons near the threshold as well as soft gluon radiation into the calculation. The calculation is done in the limit of top quark pair production at rest, i.e. $m_{t\bar{t}} \rightarrow \sqrt{\hat{s}}$. With the choice of the factorization and renormalization scales to be $\mu = m_t$ and a top quark mass of $m_t = 173.3$ GeV and the MSTW2008NNLO PDF set, a total cross section for top quark pair production at the LHC for $\sqrt{s} = 7$ TeV is calculated to be

$$\sigma_{t\bar{t}} = 162.6_{-7.6}^{+7.4}(\text{scale})_{-14.7}^{+15.4}(\text{PDF})\text{pb}. \quad (2.32)$$

Cacciari et al. [32]

These studies match approximate NNLO calculations from Ref. [33] to leading logarithm accuracy at next-to-next-to-leading order. Soft-gluon resummation at NNLL is included using two-loop anomalous dimension matrices and find only small corrections to the central value and reduction of the systematic uncertainties compared to NLL approximations. Using factorization and renormalization scales of $\mu = m_t$, a top quark mass of $m_t = 173.3$ GeV and the MSTW2008NNLO PDF set yields

$$\sigma_{t\bar{t}} = 158.7_{-13.5}^{+12.2}(\text{scale})_{-4.4}^{+4.3}(\text{PDF})\text{pb} \quad (2.33)$$

for the LHC at $\sqrt{s} = 7$ TeV.

2.3.1.2 Single Top Quark Production

With smaller production rates, top quarks can also be produced as single quarks in electroweak interactions in pp and $p\bar{p}$ collisions. Three different mechanisms contribute to single top quark production and their leading-order Feynman diagrams are shown in Fig. 2.6. The timelike production (s-channel) produces a bottom quark together with the single top quark, while in the spacelike production (t-channel) an additional, mostly light flavor, quark is produced. The third production mechanism is the production of a single top quark in association with an on-shell W boson (Wt-channel). The first observation of single top quark production was achieved by the Tevatron experiments CDF and DØ in 2009 [34, 35] and was only possible applying several multivariate analysis techniques due to the low cross sections of the processes and large backgrounds. In addition to measuring a quite rare process, the discovery of single top quark production also gives first direct access to the electroweak coupling of the top quark in form of the CKM-matrix element $|V_{tb}|$. While at $\sqrt{s} = 1.96$ TeV the Wt-channel has a negligible contribution to the combined single top quark production cross section, and the observation was made by combining s- and t-channel, the contributions from the three production mechanisms are significantly different at the LHC. The spacelike production dominates, with major additional contributions from the Wt-channel and only minor contribution from the timelike production.

Best theoretical predictions are given by approximate NNLO calculations from Kidonakis [36–38] and yield, at $\mu = m_t$ and $m_t = 172.5$ GeV with the MSTW2008NNLO PDF set, production cross sections of

$$\sigma_t = 64.57 \pm 1.33(\text{scale})_{-0.68}^{+1.38}(\text{PDF}) \text{ pb} \quad (2.34)$$

for the t-channel [36],

$$\sigma_t = 15.74 \pm 0.40(\text{scale})_{-0.68}^{+0.66}(\text{PDF}) \text{ pb} \quad (2.35)$$

for the Wt-channel [38] and

$$\sigma_t = 4.63 \pm 0.07(\text{scale})_{-0.10}^{+0.12}(\text{PDF}) \text{ pb} \quad (2.36)$$

for the s-channel [37]. In pp -collisions at the LHC the production of single top quarks dominates over the production of single antitop quarks in t- and s-channel production, corresponding to the charge asymmetry of W boson production, and the sum of both cross sections is given above. Uncertainties are obtained by varying factorization and renormalization scales between $\frac{1}{2}$ and 2 of their values and by the error set provided by the PDF of choice.

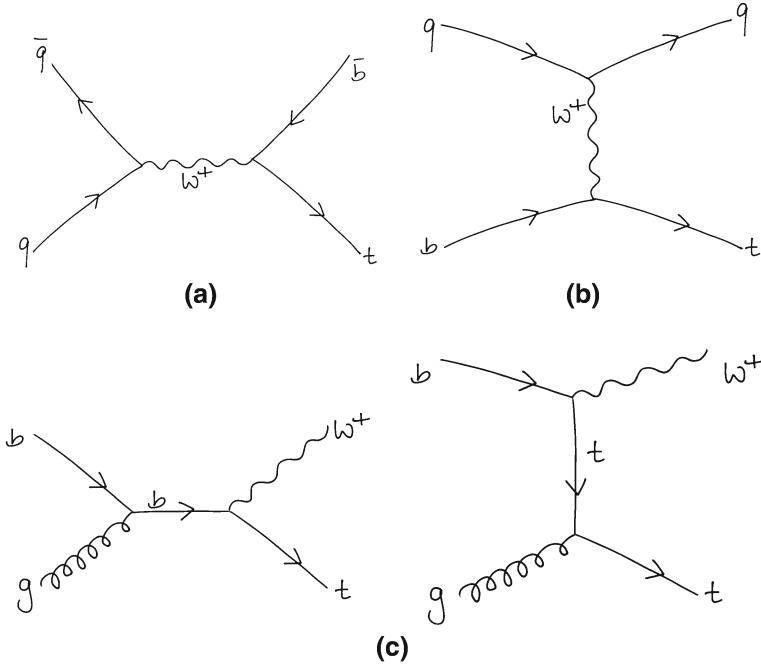


Fig. 2.6 Leading-order production mechanisms for the production of single top quarks at a pp -collider. Inversed charge currents are of course possible in the same way. (a) Timelike production of a single top quark (s-channel). (b) Spacelike production of a single top quark (t-channel). (c) Production of a single top quark in association with a W boson (Wt -channel)

2.3.2 Top Quark Decay

While top quarks can be produced both in strong (top pairs) and electroweak (single top) interactions, the decay of a top quark always obeys the principles of electroweak theory. After its short lifetime of about 0.5×10^{-24} s, the top quark decays into a W boson and a down-type quark. The probability for each type of the down-type quark to occur as decay product is given by the CKM matrix elements involving top quarks, see Eq. 2.21. Under the assumption of a unitary CKM matrix and three generations of quarks this means that top quarks decay almost uniquely into a W boson and a bottom quark ($t \rightarrow W^+ + b$ and $\bar{t} \rightarrow W^- + \bar{b}$), which can be also written in terms of branching ratios

$$R_b = \frac{\mathcal{BR}(t \rightarrow Wb)}{\mathcal{BR}(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} \approx 1 \quad (2.37)$$

and can be measured experimentally. If a deviation from the expected value for R_b is found, this would be a direct hint for an additional generation of quarks, i.e. the

need to extend the CKM matrix, or processes involving top quark decays beyond the Standard Model. Measurements were performed using events with top quark pairs both at CDF [39], which measured $R_b > 0.61$ @ 95 % C.L and $|V_{tb}| > 0.78$ @ 95 % C.L, the latter under the assumption of a SM CKM matrix, in 160 pb^{-1} of data, and DØ [40]. The DØ measurement uses significantly more data, 5.4 fb^{-1} , and measures $R_b = 0.90 \pm 0.04$ and a Standard Model value for $|V_{tb}| = 0.95 \pm 0.02$ with statistical and systematical uncertainties, showing some deviation from the Standard Model predictions. A recent measurement by the CMS collaboration, counting b -tagged jets in the dilepton channel, measures $R_b = 0.98 \pm 0.04$, consistent with the Standard Model, in 2.2 fb^{-1} of data [41]. A possibility to extend the measurements of the top quark pair production presented in this thesis to a simultaneous measurement of $\sigma_{t\bar{t}}$ and R_b , not yet measured by the ATLAS experiment, will be outlined in Chap. 8.

The events from top quark pair production and single top quark production are classified by the decay products of the W boson from the top quark decay. W bosons can decay leptonically,

$$W \rightarrow \ell \nu, \quad (2.38)$$

or hadronically,

$$W \rightarrow q \bar{q}. \quad (2.39)$$

Each possible decay occurs at the same frequency. But while the leptonic decay can occur in the three final states $(e\nu_e)$, $(\mu\nu_\mu)$ and $(\tau\nu_\tau)$, there are six possibilities for the hadronic decay. Due to its mass the W boson can produce either a $(u\bar{d})$ or $(c\bar{s})$ pair, which are always color neutral as pair and can thus form the three color combinations $(R\bar{R})$, $(G\bar{G})$ and $(B\bar{B})$. Hence, each of the nine decay modes is favored in about 11 % of all cases.

The main focus of this thesis is the top quark pair production, i.e. events with two W bosons and two bottom quarks from the top quark decays. These events can be grouped for analyses into three types with different signatures in the detector, based on the W boson decay modes.

If both W bosons decay into a pair of light quarks, the final state is called *all-hadronic* or *fully hadronic*, shown in Fig. 2.7, and the experimental signature includes two jets from b -quarks and four jets from the light quarks. In the case when only one W boson decays hadronically and the other one decays leptonically the event is referred to as *lepton+jets* or *single lepton* event.¹³ An example Feynman diagram for this process is shown in Fig. 2.8. The signature in the detector consists of four jets, two of which originating from bottom quarks, a charged lepton and a neutrino, measured as energy imbalance in the detector. The third type of events has W bosons decaying leptonically, see Fig. 2.9. In this *dileptonic* decay channel two jets from b -quarks are accompanied by two charged leptons and a significant amount of missing transverse energy, due to the two neutrinos escaping the detector. The frequency of

¹³ Or sometimes as *semileptonic* event, although the decays themselves are either strictly hadronic or strictly leptonic.

Fig. 2.7 The *allhadronic* decay mode of top quark pair production

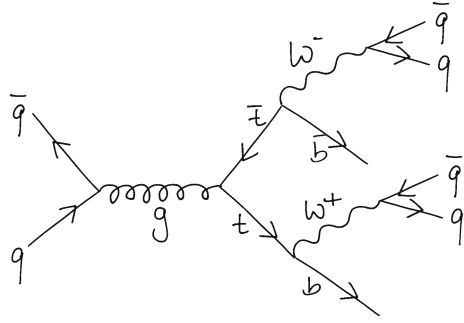
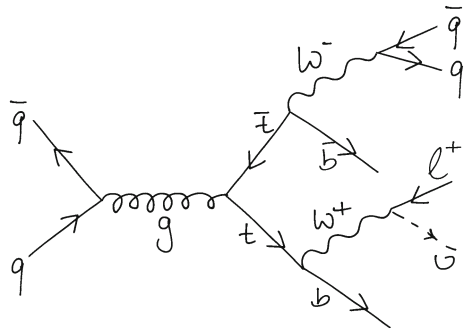


Fig. 2.8 The *lepton+jets* decay mode of top quark pair production



occurrence for each of the three classes of events can be calculated from the branching ratios of the W boson and is displayed in Fig. 2.10. Measurements in the different channels have their own advantages and disadvantages. Measurements in the all-hadronic channel are difficult to perform, since there is no charged lepton leaving a clear signature and background from QCD multijet production is large, although the process occurs at a higher rate than the other two. Dileptonic events are rather rare but have the advantage of a very clear and distinctive signature in the detector, only diluted by the missing transverse energy attributed to the two neutrinos. The channel of choice in this work is the lepton+jets channel¹⁴ offering a good trade-off between high statistics, a clear identifier from the charged lepton and missing transverse energy and manageable backgrounds.

2.3.3 Experimental Measurements of Top Quark Pair Production

The cross section for top quark pair production differs significantly between the Tevatron (7 pb^{-1}) and the LHC (165 pb^{-1}) and the top quark pairs are produced close to

¹⁴ Including events with electrons or muons and jets, as well as events with taus if the tau lepton decays leptonically.

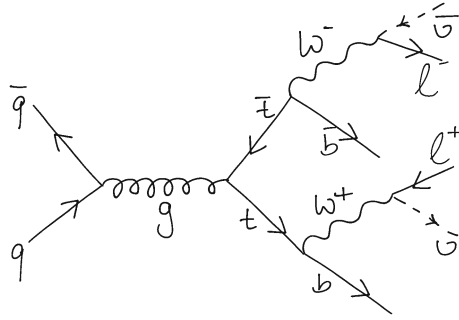


Fig. 2.9 The dilepton decay mode of top quark pair production

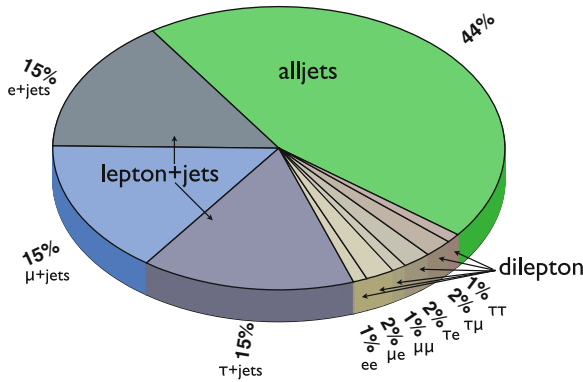


Fig. 2.10 Possible decay modes for top quark pair production and their frequency of occurrence. Most measurements in the lepton+jets and dilepton channel only include the events with τ -leptons, if they decay leptonically

the production threshold at the Tevatron and quite boosted in most cases at the LHC. Still, the main background processes and the methodology for the measurements are quite comparable. Theoretical predictions at approximate NNLO reach a precision of the order of 7 %. Similar precision is achieved by the most precise measurements using combinations of channels or in the lepton+jets channel at all experiments, including the most precise single measurement of $\sigma_{t\bar{t}}$ presented in this thesis. Most measurements are performed in the allhadronic channel, in the lepton+jets channels (e +jets and μ +jets) or a in combination of both,¹⁵ and the dileptonic channels ee , $e\mu$ and $\mu\mu$.¹⁶ However, several measurements are also performed analyzing events with hadronically decaying tau leptons or events where the charged leptons are not or not fully reconstructed.

¹⁵ Which also includes the W boson decays $W \rightarrow \tau\nu \rightarrow e/\mu\nu\nu$.

¹⁶ Again including leptonic tau decays.

Table 2.4 Most precise experimental measurements including statistical, systematic and luminosity uncertainties of the top quark pair production cross section at the experiments ATLAS, CDF, CMS and DØ

Experiment	Dileptonic		Lepton+Jets		Allhadronic	
	$\sigma_{t\bar{t}}$ (pb)	$d\sigma/\sigma$ (%)	$\sigma_{t\bar{t}}$ (pb)	$d\sigma/\sigma$ (%)	$\sigma_{t\bar{t}}$ (pb)	$d\sigma/\sigma$ (%)
CDF	$7.4^{+0.9}_{-0.9}$ [42]	12	7.82 ± 0.55 [43] ^a	7.0	7.2 ± 1.3 [44]	18
DØ	$7.36^{+0.90}_{-0.79}$ [45]	12	$7.78^{+0.77}_{-0.64}$ [46]	9.9	6.9 ± 2.0 [47]	29
ATLAS	176^{+17}_{-15} [48]	9.7	$179.0^{+11.8}_{-11.7}$ [49]	6.6	167 ± 80 [50]	48
CMS	$169.9^{+18.4}_{-18.4}$ [51]	10.8	164.4 ± 14.3 [52]	8.7	136 ± 45 [53]	33

Measurements at the LHC experiments ATLAS and CMS were performed at $\sqrt{s} = 7$ TeV, while at the Tevatron CDF and DØ experiments the production cross section was measured at $\sqrt{s} = 1.96$ TeV. All measurements assume a top quark mass of $m_t = 172.5$ GeV

^aThis analysis is somewhat different to all the others. Instead of measuring $\sigma_{t\bar{t}}$ it measures the ratio between top quark pair and Z boson production. This cancels systematic uncertainties from the luminosity determination but includes uncertainties from the theoretical Z boson cross section

Table 2.5 Combined measurements of the top quark pair production cross section as performed by the listed experiments

Experiment	Channels	$\sigma_{t\bar{t}}$ (pb)	$d\sigma/\sigma$ (%)
CDF	Dileptonic, $2 \times$ lepton+jets, allhadronic	7.50 ± 0.48 [54]	6.4
DØ	Dileptonic, lepton+jets	$7.56^{+0.63}_{-0.56}$ [45]	8.3
ATLAS	Dileptonic, lepton+jets, allhadronic	177^{+11}_{-10} [55]	6.2
CMS	Dileptonic, lepton+jets, allhadronic	165.8 ± 13.3 [56]	8.0

The most precise measurements in each of the *traditional* channels by each of the four experiments capable of measuring $\sigma_{t\bar{t}}$ are shown in Table 2.4.¹⁷

Combinations of results in the different channels are performed by all experiments at different stages. These combinations allow to exploit knowledge from statistically independent datasets with partially correlated uncertainties to gain precision. The most recent results are shown in Table 2.5. The methods applied in all channels and by all experiments follow the same principles. If possible, the dominant backgrounds are estimated directly from data and validated in control regions. Simpler methods, especially at low statistics, apply a rigid event selection optimized for a good signal-to-background ratio and count the expected background events to find the observed number of signal events and extract the cross section. More sophisticated analyses extract the cross section from a likelihood fit to a template distribution, either a single kinematic variable, like invariant masses of involved objects or secondary vertex masses, or the output of a multivariate analysis technique. Sensitivity is improved by extending the phase space and applying softer selection criteria as well as by categorizing events in classes of jet multiplicities or number of *b*-tagged jets. Incorporating some sources of systematic uncertainties as nuisance parameters in the likelihood fit can further reduce the overall uncertainty of the measurements.

¹⁷ As of March 2012.

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