Chapter 1

Top-quark physics

The third generation of quarks was first proposed by Kobayashi and Maskawa in a paper published in 1973 [1] as a way to explain the CP violation observed in Kaon decays. The existence of the third generation was confirmed when the lighter of the two constituents, the b quark, was discovered in 1977 [2].

Due to its large mass, direct confirmation of the existence of the top quark required the construction of very powerful accelerators. The top quark was discovered by the CDF and D0 experiments at Fermilab in 1995 [3, 4] and then observed at CERN in 2010 [5, 6].

The large mass of the top quark makes it a very interesting object of study. The current world average for the mass of the top quark is

$$m_t = 173.07 \pm 0.52 \text{ (stat.) } \pm 0.72 \text{ (syst.) GeV} \tag{1.1}$$

based on results from Tevatron and the LHC [7].

Due to its mass the top quark has an extremely short lifetime $\tau \approx 0.5 \times 10^{-24}$ s, too short to interact via the strong force and hadronize into a bound state [8]. Instead the top quark decays weakly producing a W boson and a b quark almost exclusively. This allows experimentalist to directly study the properties of a bare quark. An impossibility with the other quarks which bind with other quarks to form hadrons. Measurement of top quark properties (mass, charge, forward-backward asymmetry, couplings, etc...) forms a large part of high energy physics research. Measurement of these properties provide rigorous tests of the SM, point towards the existence of new physics or exclude some BSM theories.

From an experimental perspective, top quark decays can produce a very interesting signature which includes leptons, jets and transverse missing energy $\not{E}_T$ due to the escaping neutrino[1]. The study of top quark decays relies on all parts of a general purpose detector such as ATLAS or CMS. In additional $t\bar{t}$ pair production constitutes a background for many other SM and BSM searches, as such understanding this process well is fundamental for almost all areas of HEP research.

1.1 Top quark production

Top quarks can be produced in two manners, single top production and $t\bar{t}$ pair production. In the SM, the dominant top quark pair production mechanism proceeds via the strong force. The production cross-section of $pp \to t\bar{t}$ depends on the mass of the top m_t, the centre-of-mass energy $s = 4E^2_{\text{beam}}$ and the fraction of the momentum taken by the partons[2] of the colliding protons.

In order to produce a $t\bar{t}$ pair the total energy carried by the interacting partons must be larger than twice the mass of the top. Let us define the effective centre of mass energy $\hat{s}$ which reflects the true amount of energy available for interaction. Given two colliding partons, denoted i and j carrying x_i and x_j fractions of the centre of mass energy $\sqrt{s}$, then

$$\hat{s} = x_i\sqrt{s}x_j\sqrt{s} = x_i x_j s \tag{1.2}$$

assumming that both partons carry the same fraction of the total energy, i.e. $x_i \approx x_j$ then the minimum value of x required for $t\bar{t}$ production is

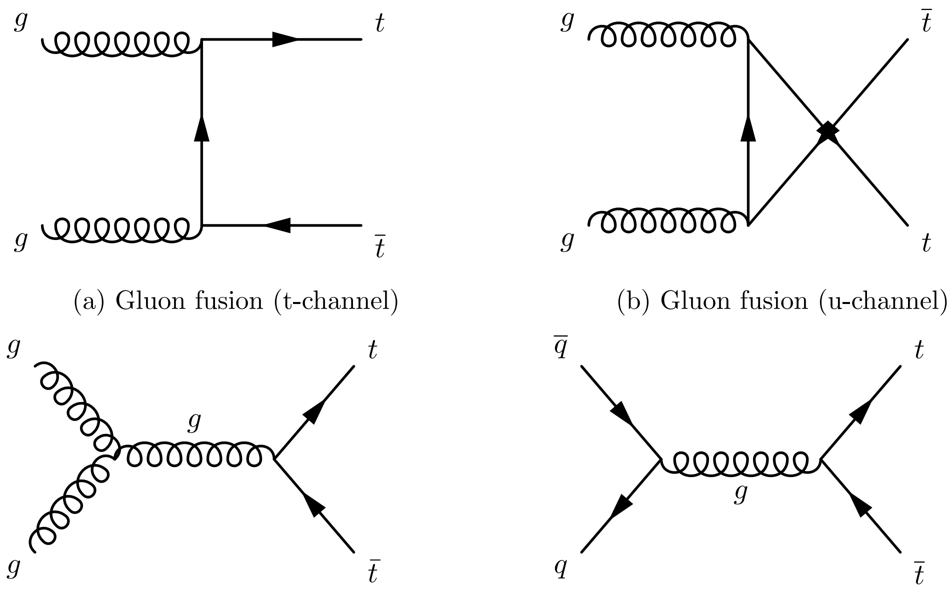
$$x \approx \frac{2m_t}{\sqrt{s}} \tag{1.3}$$

At the LHC the minimum threshold at $\sqrt{s} = 7(14)$ TeV is approximately 0.05(0.025). At such low values of x the fraction of proton momentum carried by the gluons is large [9]

[1] Neutrinos do not interact with the detector material and thus escape without being detected, missing energy is described in more detail in Chapter **??**

[2] Constituents of the hadrons, so quarks and gluons

and thus gluon fusion interactions dominate. Gluon fusion processes represent 80(90)% of the total cross section at $\sqrt{s} = 7(14)$ TeV, with the remainder contribution coming from quark pair annihilation. The feynman diagrams for these interactions are shown in Figure 1.1. The theoretical inclusive $t\bar{t}$ production cross section at the LHC has been calculated at next-to-next-to-leading order (NNLO) to be $\sigma(t\bar{t}) = 158^{-12.2}_{+13.5}$ pb [10] at $\sqrt{s} = 7$ TeV and and at next-to-leading order (NLO) 246 ± 10 pb for $\sqrt{s} = 8$ TeV.



(a) Gluon fusion (t-channel) (b) Gluon fusion (u-channel)

(c) Gluon fusion (s-channel) (d) Quark pair annihilation

Figure 1.1: The leading order Feynman diagrams for $t\bar{t}$ production.

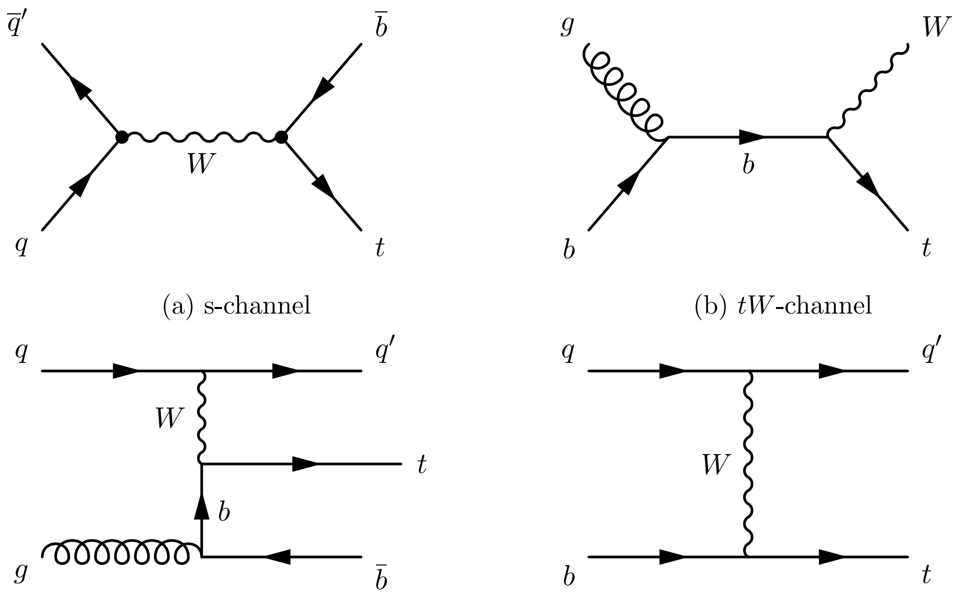
Single top production occurs via the weak force almost exclusively through the Wtb vertex since $|V_{tb}| \gg |V_{ts}|, |V_{td}|$. At LO there are several production mechanisms for single-top events:

- Weak quark-antiquark annihilation forming a W which subsequently decays into a $t\bar{b}$ (Figure 1.2a).
- The so-called tW production, where a b quark absorbes a gluon and decays to a t and W (Figure 1.2b).
- b quark scattering off a W boson, where the b comes from gluon splitting (Figure 1.2c) or from the proton (Figure 1.2d).

As top quark pair production can proceed via the strong force it occurs overwhelmingly more often than single top production. The inclusive cross-sections for $pp \to t\bar{t}$ and $pp \to t + X$ at the LHC have been estimated at NLO [11, 12]. As can be seen from Table 1.1 the production cross section of $t\bar{t}$ is approximately two times larger than the single-top cross-section.

Process	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
Single top σ(t-chan) [pb]	66 ± 2	87 ± 3
Single top $\sigma(Wt)$ [pb]	15.6 ± 1.2	22.2 ± 1.5

Table 1.1: Summary of the predicted SM single top production [11] and top pair production [12] cross sections at the LHC for $\sqrt{s}$=7 and 8 TeV.



(a) s-channel (b) tW-channel

(c) Associated with a q and $\bar{b}$ (d) Associated with a q

Figure 1.2: Example Feynman diagrams for single top quark at leading order.

1.2 Top quark decay modes

The top quark decays almost exclusively into a W boson and a b-quark. The ratio of branching ratios $\Gamma(t \to Wb)/\Gamma(t \to Wq(q = b, s, d))$ is 0.91 ± 0.04 [7].

As the LHC collides proton-proton beams, the overwhelming majority of events produced will feature multiple hadronic *jets*, a stream of particles resulting from the

Decay	Branching ratio
$W \to e + \nu$	$(10.75 \pm 0.13)\%$
$W \to \mu + \nu$	$(10.57 \pm 0.15)\%$
$W \to \tau + \nu$	$(11.25 \pm 0.20)\%$
hadrons	$(67.60 \pm 0.27)\%$

Table 1.2: Branching ratios for the decay of W boson. Note that "hadrons" refers to a possible combination of $q\bar{q}'$ where $\bar{q}'$ denotes the antiquark of a flavour different to that of the first quark. [7]

hadronization of quarks in the detector, most of which will originate from "light" quarks[3]. Unlike light hadrons, B hadrons have a sufficiently large lifetime that they travel a certain distance within a before deacying. Additional features such as the semi-leptonic decay of b quarks can be exploited to determine the presence of such a quark in the detector. Collectively analysis techniques that permit the detection of b-jets are known as *b-tagging*. Top quark events will produce two b quarks, making b-tagging techniques a central part of any $t\bar{t}$ analysis.

The other part of the top decay, the W boson is used to classify $t\bar{t}$ events. As discussed in Section **??**, W bosons can decay leptonically ($\ell\nu_\ell$) or hadronically ($W \to q\bar{q}'$) driven by the CKM vertex element, since $\Gamma \propto |V_{ij}|^2$. The various branching ratios of W decays are presented in Table 1.2.

Thus $t\bar{t}$ events are labelled as "dilepton", "all-hadronic" or "lepton + jets" depending on the combination of W decays present. The probability for $t\bar{t}$ event to be of a given type is dependent on the branching-ratios of W decays shown a priori. As can be seen from Figure 1.3 the all-hadronic events dominate, followed by the lepton plus jets and dilepton. Each of these types requires a very different analysis approach due to their distinct backgrounds, branching-ratio, detector signature and reconstruction requirements.

The all-hadronic final state includes four light quarks which will hadronize to form four Light Flavour (LF) jets and two b quarks leading to two b jets. Due to the large hadronic activity the all-hadronic channel is very challenging. As mentioned before, hadronic collisions produce events with a large number of quarks – and thus jets – in the final state. The background to the all-hadronic channel are therefore very high. As

[3]The term light quarks usually refers to quarks in the first two generations. Light jets are those originating from those quarks

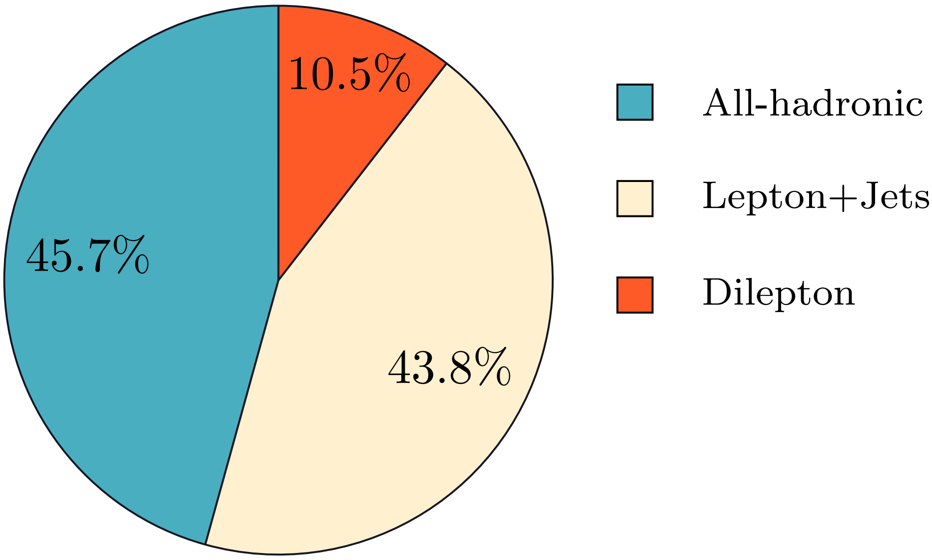


Figure 1.3: Branching ratios of all possible $t\bar{t}$ decays. These probabilities are based on the branching-ratios of W decay shown in Table 1.2.

shown in Figure 1.3, the all-hadronic channel has the largest branching ratio of the three.

The dilepton final state includes two leptons, large $\not\!\!E_T$ from two neutrinos which escape the detector and two b jets. In constrast to the all-hadronic channel, dilepton events are very clean due to the presence of leptons and $\not\!\!E_T$, however the branching ratio is very small and reconstruction of the top is challenging due to the presence of two neutrinos which escape the detector without interacting.

Finally, the lepton plus jets channel has a large branching ratio while having a distinct signature with a lepton and $\not\!\!E_T$ as well as LF and b jets. Lepton plus jets analyses usually do not directly include τ leptons as the signal lepton. The τ lepton is unstable and decays primarily via the weak force producing hadrons in the final state. The reconstruction of τ leptons is a complex task and τ plus jet events are treated separetely within dedicated analyses. An example of the full lepton plus jets chain is shown in Figure 1.5.

The lepton plus jets channel has the advantage of a more distinct signature than the all-hadronic event as well as a suffering from less background. Additionally the branching ratio of lepton plus jets event is approximately twice that of the dilepton channel. As a result the lepton plus jets channel has been chosen as the focus of this thesis.

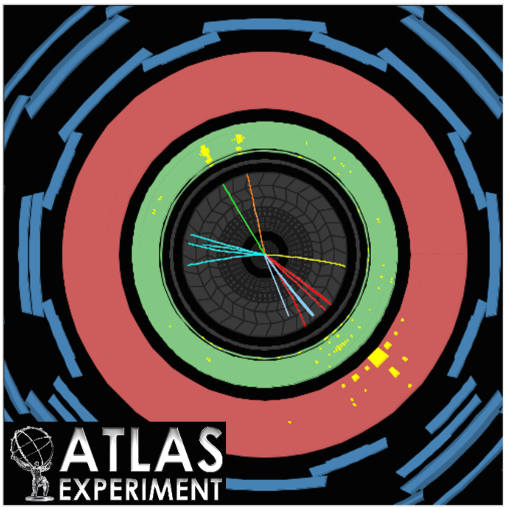


Figure 1.4: Example event display of a dilepton $t\bar{t}$ event recorded by ATLAS.

Figure 1.5: The feynman diagram of lepton plus jets channel including $t\bar{t}$ production via gluon fusion and decay with a leptonically decaying W^+. Note that all other production mechanisms are also considered and the final state where the W^- is decayed leptonically is also taken into account.

1.3 Latest developments in top physics

This section discusses a few of the latest measurements in the area of top quark pair production with a focus on LHC results. As discussed top quark decays provide the only probe to study the properties of a bare quark. Measurements of its properties provide a stringent test of the SM and could show hints of new physics from BSM theories. Moreover, due to its final state signature, top quark pair production, particularly in the lepton + jets channel, form the background to many searches for new physics. Additionally all parts of the detector are utilized in the reconstruction of ℓ+jets events and as such it is possible to use these events to tune or *calibrate* many analysis and reconstruction techniques.

Cross-section measurement

Measurement of the cross-section of the top quark is a benchmark test of the SM. Any statistically significant deviation from the predicted value could point to the presence of new physics. Some BSM theories posit the existence of particles which could decay to produce a $t\bar{t}$ pair. If such theory is correct this would be observed in an increase in the cross section measured away from the predicted SM value.

Experimentally measurement of the cross-section is vital when attempting to reduce and estimate the amount of top quark background present in other analyses. Searches for the Higgs boson exploit many different channels such as $t\bar{t}H \to t\bar{t}b\bar{b}$ which have $t\bar{t}$ events as a background. The type of events predicted by the BSM theory, Supersymmetry (SUSY) include a large amount of $\not{E}_T$, leptons and jets in the final state. Top quark pair events mimmick these processes and constitute a large background.

A summary of all $t\bar{t}$ cross section measurements from the LHC is shown in Figure 1.6 and a comparison against the Tevatron measurement at $\sqrt{s} = 1.96$ TeV is shown in Figure 1.7.

Top mass measurement

The mass of the top m_t is a fundamental parameter of the SM. ake sure to fill this in!!!

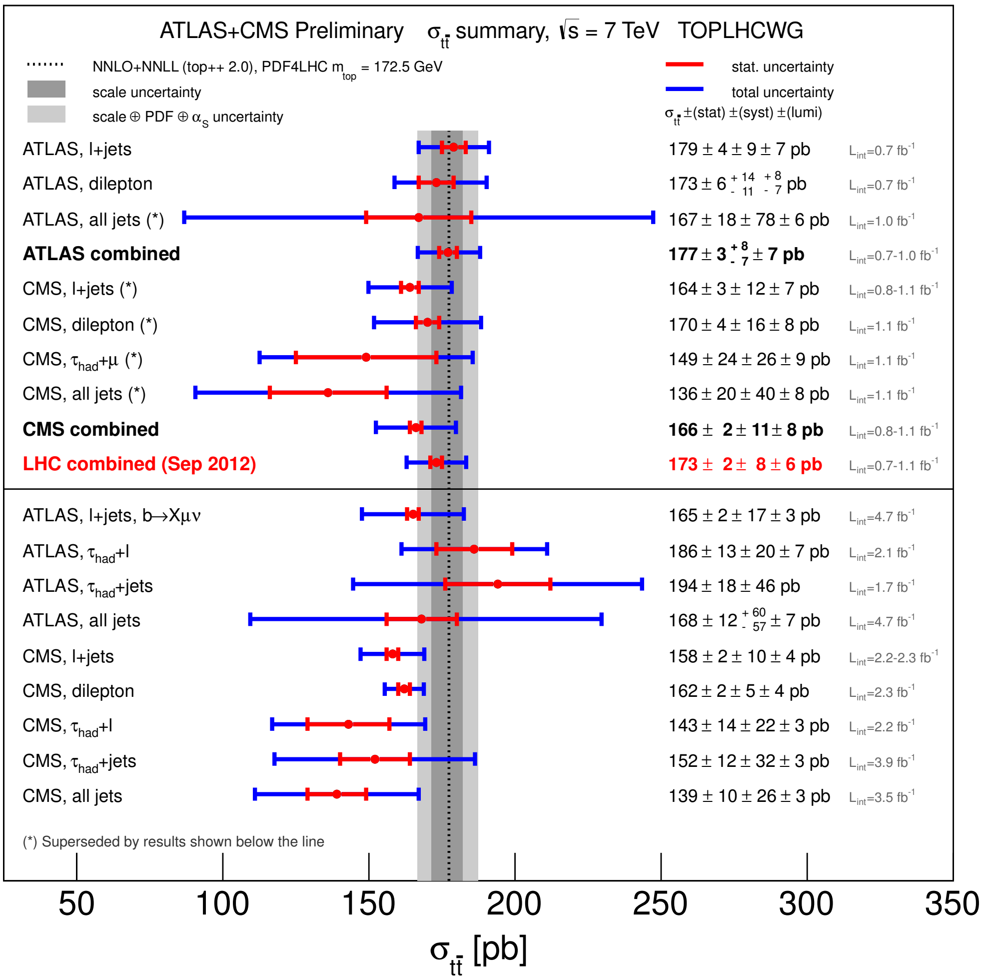


Figure 1.6: A summary of all $t\bar{t}$ production cross section measurements performed at the LHC at $\sqrt{s} = 7$ TeV. Note the theory prediction shown as a dotted black line with its associated uncertainties as grey bands. The results shown above the black line have been statistically combined, producing the results labelled as **combined**. Many of these analyses have been superseded and the results are shown below the line. Other analyses performed but not included in the combination are also shown below the line.

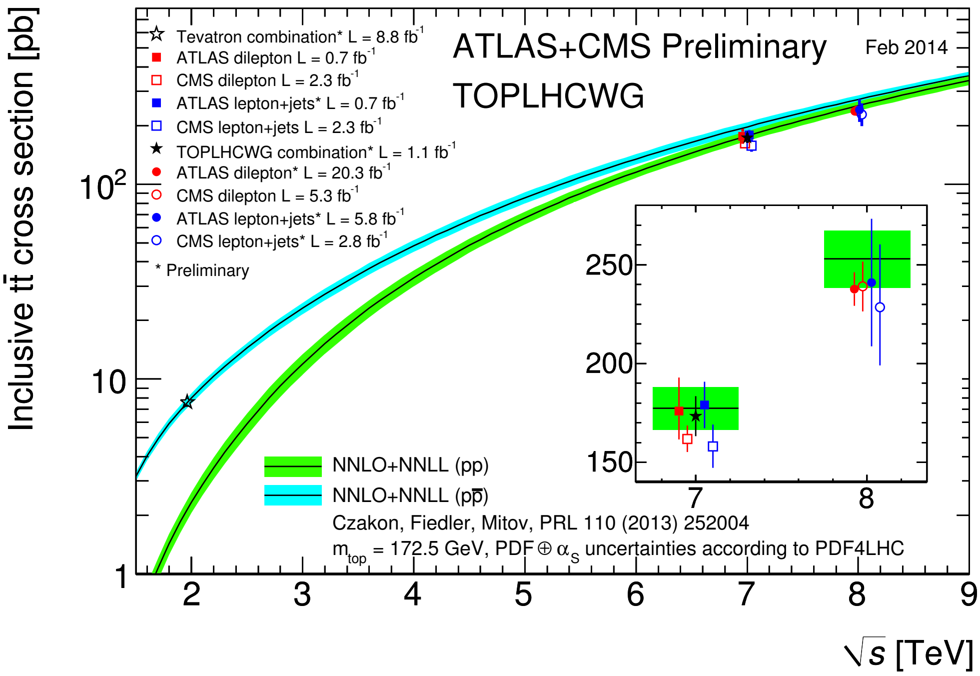


Figure 1.7: A summary of the most precise $t\bar{t}$ production cross section measurements performed at the LHC at $\sqrt{s} = 7$ and 8 TeV and the Tevatron at $\sqrt{s} = 1.96$ TeV compared to the theoretical prediction. Note that the Tevatron results should be compared against the prediction for $p\bar{p}$ collisions while the LHC against the pp collision predictions.

Mass asymmetry measurement

As discussed, in Section **??**, the charge (C) and parity (P) symmetries are both violated in weak interactions. The CPT symmetry which includes time reversal (T) is the last remaining symmetry which no interaction appears to violate. Any deviations from this symmetry would have major implications on particles physics [13] and could manifest itself as differences between matter and antimatter particles. As the only quark which can be studied directly, measurement of $\Delta m \equiv m_t - m_{\bar{t}}$ could hint at any such deviation produced by new physics. Such a measurement was conducted by the ATLAS [14] experiment yielding the result:

$$\Delta m_t = -0.44 \pm 0.46 \text{ (stat.) } \pm 0.27 \text{ (syst.) GeV} \tag{1.4}$$

and by the CMS [15] experiment yielding the result:

$$\Delta m_t = 0.67 \pm 0.61 \text{ (stat.) } \pm 0.41 \text{ (syst.) GeV} \tag{1.5}$$

which are both consistent with the SM prediction and imply CPT invariance.

Boosted top searches

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