The top and beyond: missing energy and little Higgs in ATLAS
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Phenomenology and Simulation of Proton Collisions

In preparation of collision data from the LHC, the expected interactions in proton-proton collisions and their expected signature in the ATLAS detector are studied in simulated events. Apart from providing an environment to develop analysis strategies and estimate the discovery potential of new physics scenarios, the simulation is vital for the development of reconstruction algorithms (cf. Chapter 4). The simulation and reconstruction of events in ATLAS is performed in the Athena framework [36]. This software suite handles the following steps:

- **Event generation**: simulation of the proton collisions. It takes care of the production and decay of particles in a given process;

- **Detector Simulation**: describes the interaction and energy losses of the generated particles when traversing the active and inactive parts of the detector;

- **Digitization**: simulates the detector readout, i.e. the conversion of energy deposits in the detector to times, currents and voltages;

- **Reconstruction**: consists of algorithms that employ pattern recognition, track fitting, calibration, et cetera on the detector readout to construct primary physics objects. These algorithms are applied to simulated data and collision data in exactly the same manner. This step is fully described in Chapter 4.

Section 3.1 describes the properties of hadronic collisions that are relevant for Monte Carlo event generators, some of which are subsequently presented in Section 3.2. Section 3.3 presents all Monte Carlo samples that are used in the analyses in the following chapters. The simulation of the ATLAS detector response is briefly discussed in Section 3.4.

### 3.1 Phenomenology of Proton Collisions

Protons are baryons composed of two up quarks and a down quark, which are the valence quarks, plus additional virtual quark-antiquark pairs and gluons which constitute the sea.
For the generation of processes that occur in proton-proton collisions, the basic ingredients are related to the manifestations and limitations of (perturbative) QCD. The main aspects are reviewed here.

### 3.1.1 The Running Coupling

When calculating physical observables from the Standard Model Lagrangian, all Feynman diagrams with the initial and final state of interest need to be summed over. Often this involves divergent contributions from loop diagrams. The final result, however, is a measurable and thus finite quantity due to the cancellation between divergencies from different diagrams. In practice, calculations can be performed up to a limited amount of loop corrections only and some divergent diagrams are left uncancellation. The antidote is to absorb the infinities into physical parameters such as mass or coupling strength. In this renormalization procedure, the infinities are separated from the finite contributions first by means of a regularization scheme. When performing calculations up to a fixed order, the result depends on the regulator, which is traded for the renormalization scale $\mu_R$. It parameterizes the extend to which loop corrections that are not taken into account affect the physics.

Since the renormalization scale $\mu_R$ is entirely arbitrary, no physical observable $O$ should depend on it, i.e.

$$
\mu_R^2 \frac{\partial}{\partial \mu_R^2} O(Q^2/\mu_R^2, \alpha) = \left[ \mu_R^2 \frac{\partial}{\partial \mu_R^2} + \mu_R^2 \frac{\partial \alpha}{\partial \mu_R} \frac{\partial}{\partial \alpha} \right] O(Q^2/\mu_R^2, \alpha) = 0.
$$

The dependence of the coupling $\alpha$ on the scale $\mu_R$ is described by the $\beta$-function, which can be calculated order by order in perturbation theory:

$$
\mu_R^2 \frac{\partial \alpha}{\partial \mu_R} \equiv \beta(\alpha) = -\alpha \sum_i \beta_i \left( \frac{\alpha}{4\pi} \right)^{i+1},
$$

As it is no longer a constant, $\alpha(\mu_R)$ is referred to as the *running coupling*.

Neglecting all but the leading order contribution, the following differential equation follows from \(3.2\)

$$
\mu_R^2 \frac{\partial \alpha}{\partial \mu_R} = -\beta_0 \frac{\alpha^2}{4\pi}.
$$

The solution is readily found by integration to be

$$
\alpha(\mu^2) = \frac{\alpha(\mu_0)}{1 - \frac{3}{2\pi} \alpha(\mu_0) \ln \frac{\mu^2}{\mu_0^2}}.
$$

which means that the coupling strength at any scale $\mu$ is related to the coupling strength at a reference scale $\mu_0$. For the QCD coupling $\alpha_s$, the first four coefficients of the $\beta$ function
3.1 Phenomenology of Proton Collisions

are presently known, yet we focus on the first coefficient, $\beta_0$, which is given by

$$\beta_0(\alpha) = -\frac{4}{3}$$ (3.5)

$$\beta_0(\alpha_s) = 11 - \frac{2}{3}n_f$$ (3.6)

for the QED and QCD coupling strengths respectively. The latter depends on the number of quark flavours $n_f$ that are relevant in the calculation at hand. Its value is maximally six though and the coefficient is positive. Consequently, the strong coupling strength decreases with increasing energy scales whereas the electromagnetic coupling strength exhibits the opposite behaviour.

The reference scale $\mu_0$ is often set equal to the mass of the $Z$ boson, at which the values of the coupling strengths are determined to be $[10]$ $\alpha(m_Z^2) \approx \frac{1}{127}$ (3.7)

$$\alpha_s(m_Z^2) = 0.1184 \pm 0.0007$$ (3.8)

Both values are the world average of a large number of independent consistent measurements.

Two important properties of QCD are direct consequences of the behaviour of the strong coupling $\alpha_s$:

- **Asymptotic freedom** is the property of quarks and gluons to behave as free particles at very short distances. As opposed to the electromagnetic coupling, the strength of the strong coupling decreases with increasing energy scale $\mu_R$ and within a hadron, the partons interact weakly. As a consequence, the parton model $[37]$, which treats the partons as free and non-interacting, turns out to describe hadrons sufficiently well. An important consequence of asymptotic freedom is the fact that perturbation theory can be applied at high energy scales.

- **Colour Confinement** is the phenomenon that partons are tightly bound together in colour neutral combinations, hadrons, and rapidly recombine into such combinations when forced apart by highly energetic collisions. Consequently, no quarks or gluons are observed directly in experiment. The corresponding energy scale is denoted $\Lambda_{\text{QCD}}$:

$$\lim_{\mu_R \to \Lambda_{\text{QCD}}} \alpha_s(\mu_R^2) = \infty.$$ (3.9)

3.1.2 Factorization

According to the factorization theorem $[38]$, the cross section for hadronic collisions is well described by the convolution over functions describing the long distance dynamics and functions describing the hard process. The separation is specified by the factorization scale $\mu_F$.

The cross section of proton-proton scattering is therefore expressed in terms of the interaction between two incoming partons, $q_a q_b \to X$:

$$\sigma_{pp \to X} = \sum_{a,b} \int \mathrm{d}x_1 \, \mathrm{d}x_2 \, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \hat{\sigma}_{q_a q_b \to X}(x_1, x_2, \alpha_s(\mu_R^2), \mu_F^2) + O\left(\frac{\Lambda_{\text{QCD}}^2}{Q^2}\right),$$ (3.10)
where $Q^2 = -q^2$ is the process dependent momentum transfer in the hard interaction, $x_{1,2}$ are the fractions of proton momenta carried by the two initial state partons, and $f_a(x, \mu_F^2)$ are the parton distribution functions (PDFs). They describe the probability density for a parton with flavour $a$ to carry a fraction $x$ of the longitudinal momentum of the proton, when probed at a scale $\mu_F^2$. In practice, the PDF is often transformed into the parton momentum density by means of a multiplication with the momentum fraction $x$. By definition, the contributions of all partons sum up to unity, i.e.

$$\sum_a \int_0^1 dx \, xf_a(x, \mu_F^2) = 1.$$  \hspace{1cm} (3.11)

Both the factorization scale $\mu_F^2$ and the renormalization scale $\mu_R^2$ are commonly set to the characteristic scale of the process, $Q^2$. Because of the non-perturbative nature of QCD bound states, PDFs cannot be derived from calculations and they are extracted from data obtained at previous generations of collider experiments instead. Several realizations of such parameterizations exist, all containing a major input contribution from electron-proton collision data recorded by the detectors at HERA \[39\]. Figure 3.2 shows the behaviour of $xf_a(x, Q^2)$ for each parton flavor according to the CTEQ parametrization \[40\], which is used as the default. The density increases at lower values of $x$ as the scale $Q^2$ increases, which is illustrated by the comparison between the parton momentum densities at $Q^2 = 4 \text{ GeV}^2$ (left) and at $Q^2 = 10^4 \text{ GeV}^2$ (right).

The momenta involved in the partonic process, $q_a q_b \rightarrow X$, are high and at this scale the strong coupling $\alpha_s(Q^2)$ is small enough for perturbation theory to be valid. The partonic cross section is expressed as a power series in the expansion parameter $\alpha_s(Q^2)$:

$$\hat{\sigma}(x_i, x_j, Q^2) = \sum_{n=0}^{\infty} \hat{a}_n \alpha_s^n(Q^2).$$  \hspace{1cm} (3.12)

This expression is well defined and the coefficients are in principle calculable to all orders by means of Feynman rules. In practice, however, the order to which the calculations are
3.1 Phenomenology of Proton Collisions

Figure 3.2: Parton momentum density parametrizations according to CTEQ [40] for two different energy scales as a function of the momentum fraction $x$ of the proton carried by each parton flavour.

performed is severely limited as the number of additional diagrams to be calculated increases rapidly with each order. The main contribution to the amplitude of a given process are the diagrams with the lowest power in the expansion parameter, which are generally tree level diagrams. They contribute at leading order (LO) to the partonic cross section. In case of $t\bar{t}$ production, these diagrams contain two QCD three-vertices and contribute at order $O(\alpha_s^2)$ (cf. Figure 3.3). At next-to-leading order (NLO), diagrams with an additional power of the expansion parameter come into play, for instance due to real or virtual gluon emission. The size of the contributions are suppressed by the additional power of the expansion parameter, yet the number of diagrams increases. Most importantly, the dependence on the renormalization scale and the corresponding uncertainty on the cross section decrease when including the additional diagrams.

Additional Phenomena

The partons that take part in the hard process are colour charged and therefore subject to gluon emission. Usually, a distinction is made between radiation from the incoming partons, which is called initial state radiation, and radiation from the outgoing partons, which is called final state radiation. The emitted gluons split into quark/anti-quark pairs or gluon pairs et cetera, which may result in cascades of additional partons. These cascades are described by parton showering models.

When partons created in these processes move away from each other, the colour field between them increases and quark/antiquark pairs are created from the vacuum. Hadronization is the process where the partons combine into colour neutral states, hadrons, which are energetically favourable. Hadronization occurs at a much later time scale than the hard process and the corresponding energy scale is too low for perturbation theory to be valid. The non-perturbative description is modelled by fragmentation functions, which are the final state equivalent of PDFs.
The resulting hadrons, in turn, are often unstable and decay further into stable particles, which eventually interact with the ATLAS detector.

### 3.2 Monte Carlo Generators

Monte Carlo (MC) generators are computational algorithms that make use of random numbers to simulate systems in nature that behave stochastically. In collider physics, they are applied in the simulation of events as produced in collisions. On an event by event basis, the properties of each particle involved are determined by expected probability densities using random number generators. These techniques are indispensable when describing the expected interactions between particles because the complexity of the corresponding phase space integrals is such that analytic calculations are not feasible.

MC generators make use of the factorization principle and the various elements in the description of the collisions are considered independently. First, the matrix elements corresponding to the hard process are calculated perturbatively. The decays of short-lived resonances produced in parton collisions, e.g. top quarks or $W'$ bosons, are regarded as part of the hard process. Presently, matrix element event generators up to NLO are available. Monte Carlo techniques are utilized to generate the momenta of the incoming partons according to their PDFs.

Subsequently, initial and final state radiation are simulated according to a parton showering model, in which splitting functions are used to describe the probability for a parton to split into two partons. The splitting functions are derived from QCD, albeit in a tree level approximation.

No descriptions from first principles exist for hadronization nor for hadron decays. These processes are implemented in MC generators via phenomenological models.

There are several possibilities to model parton showering and hadronization. In addition, various methods exist to combine the matrix elements from the hard process with the modelled behaviour of the soft phenomena. As a consequence, a long list of MC generators is available, a subset of which is listed here:

**Pythia** [41] is an event generator capable of performing the full simulation chain and a large range of hard processes is available at LO. The hadronization process is described by the string fragmentation model [42], in which the colour field between partons is represented by a string potential.

**Herwig** [43] is the second major event generator that takes care of the full simulation chain, but uses a slightly different approach for parton showering and for hadronization than Pythia. The cluster fragmentation model is employed in the hadronization step, in which gluons are split into quark pairs and combined with neighbouring quarks into colour neutral clusters.

**MCatNLO** [44] is a specialized matrix element generator, which calculates the matrix elements of the hard process up to NLO. It is interfaced with Herwig for the parton showering and an advanced matching scheme is applied to prevent double counting of gluon emissions.
3.3 Event Samples for $t\bar{t}$ and $W' \rightarrow tb$ Analyses

**Alpgen** is a specialized matrix element generator that generates tree level matrix elements for processes with up to six additional final state partons. Interfaces to both Pythia and Herwig are available to perform the parton showering.

**AcerMC** is another matrix element generator optimized for the simulation of background processes. The matrix element calculation can be interfaced to Pythia as well as Herwig for parton shower development.

The kinematic distributions for a given process may differ between the MC generators. Extensive studies on the comparison have been performed for instance in [47, 48]. When available, the NLO matrix elements are preferred over LO, yet the different phenomenological descriptions of the soft phenomena are used in parallel. Eventually, each of the MC generators will be tuned to the LHC data by means of free parameters, as will the PDFs. The final level of agreement may provide insight in the best choice of hadronization model.

**Parton Multiplicities**

The event generator Alpgen is specialized in the generation of multi-parton hard processes with up to six final state partons. The distance between the generated partons is required to satisfy $\Delta R > 0.7$ and their transverse momenta satisfy $p_T > 15$ GeV. The multi-parton hard process is complemented with parton showering to describe the additional radiation. This procedure has to be considered with care in order to prevent double counting. An event with $N$ final state partons can be obtained by several configurations of the number of hard partons and the number of showered partons. This is taken care of by the so called MLM matching scheme [49], in which final state jets (cf. Section 4.2) are matched to the hard partons with $\Delta R < 0.7$ and events are vetoed in case not all jets and partons are matched bijectively. Only in the sample with the highest hard parton multiplicity, additional jets from showering are allowed to be present.

### 3.3 Event Samples for $t\bar{t}$ and $W' \rightarrow tb$ Analyses

The simulated events that are studied in Chapters 4, 5 and 6 are $t\bar{t}$ events, i.e. proton collisions that result in a top/antitop quark pair. The MC generation of these events and relevant background events is discussed in Section 3.3.1. Chapter 7, on the other hand, focuses on the production of $W'$ bosons in the context of Little Higgs models and in particular the decay channel $W' \rightarrow tb$. The generation of these events is the subject of Section 3.3.2.

The majority of the MC samples are produced and validated centrally by the ATLAS collaboration. For the analysis of $t\bar{t}$ events, all samples are available in full detector simulation, i.e. with GEANT4, which is described in Section 3.3. For the analysis described in Chapter 7, two samples with $W' \rightarrow tb$ events are generated privately with Pythia [41]. In this case, the software used for the simulation of the detector response is ATLFAST II (cf. Section 3.4).
3.3.1 Samples for $t\bar{t}$ Analysis

Production of $t\bar{t}$ Events

Figure 3.3 shows the four diagrams that contribute to the production of top quark pairs at leading order (LO). At the high LHC beam energies, partons with small momentum fractions $x$ contribute significantly to the production of $t\bar{t}$ events. Figure 3.2 shows that the PDF for gluons dominates in this region. As a consequence, the three diagrams with initial state gluons give the main contribution.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{feynman_diagrams.png}
\caption{The Feynman diagrams that contribute at leading order to the production of $t\bar{t}$ events.}
\end{figure}

Semileptonic $t\bar{t}$ Events

Each top quark decays into a $W$ boson and a $b$ quark, as other decay channels are strongly suppressed by the corresponding entries of the CKM matrix. In Chapters 5 and 6, semileptonic $t\bar{t}$ events are selected, i.e. events in which one of the $W$ bosons decays leptonically ($t \to Wb \to l\nu b$), while the other decays hadronically ($t \to Wb \to qq'b$).

Because of fermion universality in weak interactions, in approximately 1/3 of the cases the $W$ boson decays leptonically, i.e. into a charged lepton and the corresponding neutrino, and the remaining 2/3 are hadronic decays, i.e. into a pair of quarks. This results in a classification of three types of decays, namely hadronic, semileptonic and dileptonic $t\bar{t}$ decays. The corresponding branching ratios are 45.7 %, 43.8 % and 10.5 % respectively, as follows from the individual branching fractions of the $W$ boson decay modes according to the PDG [11]. The share of each type of decay is schematically illustrated in Figure 3.4.

The reconstruction, the characteristics and the selection of semileptonic $t\bar{t}$ events are described in detail in the following chapters. In short, the final state contains a single charged lepton, four quarks (when ignoring initial and final state radiation) and a neutrino.

The sample of $t\bar{t}$ events is generated with MCatNLO. At the event generation stage, the decay of the top quarks is restricted such that at least one of them decays leptonically. As a consequence, the sample consists of both semileptonic and dileptonic $t\bar{t}$ events and the corresponding cross sections are determined from the branching fractions. Although the dileptonic events are contained in the same sample for production convenience, they are considered as background in the analysis.

Backgrounds to $t\bar{t}$ Events

Apart from dileptonic $t\bar{t}$ events, the following processes are expected to exhibit signatures in the ATLAS detector similar to semileptonic $t\bar{t}$ events and are considered as background:

\footnote{All Feynman diagrams are drawn with the use of Axodraw [50].}
3.3 Event Samples for $t \bar{t}$ and $W' \rightarrow tb$ Analyses

- **$W + \text{jets}$**: The largest contribution is expected from $W$ boson production in association with jets, where the $W$ boson decays leptonically. Additional jets originate from gluon radiation, which at times in fact results in the exact same composition of final state objects as $t \bar{t}$ events. The cross section does decrease with increasing numbers of additional jets.

- **multi-jet**: In proton-proton collisions, any two initial state partons may interact through a QCD 3-vertex and the intermediate parton in turn splits into another two outgoing partons. Each incoming and outgoing parton may radiate additional quarks and gluons, resulting in a final state with large hadronic activity. These type of events are hereafter referred to as multi-jet events, with the exception of events where the two outgoing partons are both top quarks. The latter are treated separately, namely as $t \bar{t}$ events.

The predicted inclusive cross section for multi-jet events is enormous compared to $t \bar{t}$ production, since the relatively heavy top quarks require a minimum value of $x_1 x_2 s$ to be produced. In fact, the uncertainty on the multi-jet cross section is large due to the fact that loop corrections are ignored in the calculation and because large powers of $\alpha_s$ are involved. Nevertheless, the only multi-jet events that contribute as a background are the small fraction in which a lepton is reconstructed in the final state. Therefore, in order to save computing time, the generated MC samples include a filter, which is described below. One sample is produced specifically for the electron channel and one for the muon channel analysis.

- **single top**: Figure 3.5 displays the LO diagrams for single top production. Since the weak interaction is involved in the production, the cross sections are small compared to $t \bar{t}$ production. The generated MC samples are restricted to contain leptonically
decaying top quarks only.

Figure 3.5: The Feynman diagrams corresponding to single top production at LO via the s-channel (left), the t-channel (middle) and the Wt channel (right).

Monte Carlo Samples and Cross Sections

Table 3.1 contains the cross sections and applied filters for all event samples relevant to the semileptonic $t\bar{t}$ event selection. The first column indicates the integrated luminosity that corresponds to the samples, given the number of generated events. The studies performed in this thesis are all based on Monte Carlo simulations of proton collisions at 10 TeV center of mass energy, with the exception of the very last chapter. For comparison, the cross sections corresponding to the design collision energy of 14 TeV are given in Table 3.1 as well. It is observed that the signal to background ratio will improve a great deal as soon as the design collision energy of 14 TeV is reached. The $t\bar{t}$ production cross section is most sensitive to $\sqrt{s}$ due to the threshold on $x_1x_2s$ required to produce the massive top quarks.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\int L$ (pb$^{-1}$)</th>
<th>Filter</th>
<th>$\sigma$(10 TeV)</th>
<th>$\sigma$(14 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>semileptonic $t\bar{t}$</td>
<td>1250</td>
<td>none</td>
<td>176</td>
<td>387</td>
</tr>
<tr>
<td>dileptonic $t\bar{t}$</td>
<td>1250</td>
<td>none</td>
<td>42.2</td>
<td>92.7</td>
</tr>
<tr>
<td>$W +$ jets (e)</td>
<td>$\sim$900</td>
<td>3jet</td>
<td>377</td>
<td>505</td>
</tr>
<tr>
<td>$W +$ jets (µ)</td>
<td>$\sim$900</td>
<td>3jet</td>
<td>120</td>
<td>168</td>
</tr>
<tr>
<td>$W +$ jets (τ)</td>
<td>$\sim$900</td>
<td>3jet</td>
<td>221</td>
<td>181</td>
</tr>
<tr>
<td>single top</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>leptonic s-channel</td>
<td>$\sim$8000</td>
<td>none</td>
<td>2.27</td>
<td>3.45</td>
</tr>
<tr>
<td>leptonic t-channel</td>
<td>$\sim$8000</td>
<td>none</td>
<td>43.4</td>
<td>79.9</td>
</tr>
<tr>
<td>semi- and dileptonic Wt</td>
<td>175</td>
<td>none</td>
<td>14.3</td>
<td>35.8</td>
</tr>
<tr>
<td>multi-jet (e)</td>
<td>9.6</td>
<td>top-µ</td>
<td>$2.10 \cdot 10^6$</td>
<td></td>
</tr>
<tr>
<td>multi-jet (µ)</td>
<td>9.6</td>
<td>top-µ</td>
<td>$108 \cdot 10^3$</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: The cross sections for $\sqrt{s} = 10$ TeV and $\sqrt{s} = 14$ TeV respectively. The numbers include the efficiencies of the applied filters, which are described in the text.

Filters

Only a fraction of the $W+$jet and multi-jet events actually contributes to the background in a $t\bar{t}$ analysis. In order to save computing time, events are pre-selected already at event
3.3 Event Samples for $t\bar{t}$ and $W' \rightarrow tb$ Analyses

generation level. Despite the enormous cross section, the generation of multi-jet becomes feasible in terms of computing time when such a filter is included. The applied filters are designed specifically for studies involving $t\bar{t}$ events [17]:

- **3jet**: The presence of at least three jets reconstructed by Cone4TruthJets (cf. Section 1.2) that satisfy $p_T > 30$ GeV is required.

- **top$_{\mu}$**: At least one muon is present with $p_T > 10$ GeV and $|\eta| < 2.8$.

- **top$_{\text{jet}}$**: At least four jets reconstructed with Cone4TruthJets are present, satisfying $p_T > 17$ GeV and $|\eta| < 5.0$, while at least three jets are reconstructed with Cone4TruthJets that satisfy $p_T > 35$ GeV and $|\eta| < 5.0$.

For all processes involving $W$ bosons, the branching fractions of the leptonic decay is equal for each lepton flavour. This does not hold for the numbers in Table 3.1 for the $W +$ jets samples as a consequence of the varying efficiency of the 3jet filter, which is why they are mentioned separately for each lepton flavour. The efficiency of the filter is largest on the muon channel as muons do not result in jets reconstructed with Cone4TruthJets as often as electrons and taus.

Both the $W+$jet and multi-jet samples are generated with the event generator Alpgen, as it specializes in the generation of multi-parton hard processes (cf. Section 3.2). In the hard process, only the first two generations of quarks are represented and the $b\bar{b}$ pairs that result from parton showering are generally restricted to low values of $p_T$. In order to cover the phase space properly, the separate processes $W+b\bar{b}$+jets and $b\bar{b}$+jets are generated with the restrictions $p_T(b) > 20$ GeV and $\Delta R(b, \bar{b}) > 0.7$ to complement the default $W+$ jets and multi-jet samples.

3.3.2 Samples for $W' \rightarrow tb$ Analysis

In Chapter 4 the aim is to select events in which a $W'$ boson decays into a top and a bottom quark, where the top quark decays leptonically. The notation $W' \rightarrow tb$ is used hereafter to indicate the sum of the decay modes $W'^+ \rightarrow t\bar{b}$ and $W'^- \rightarrow \bar{t}b$. The $W'$ boson is produced in proton-proton collisions through the interaction of two quarks, as depicted in Figure 3.6. The production cross section in proton collisions is small as the $q'\bar{q}$ initial state involves a sea parton and high values of the momentum fractions $x_1$ and $x_2$ are required for the massive $W'$ boson to be produced.

![Figure 3.6: Feynman diagram of the production of $W'$ at LO.](image-url)
Two private samples are produced with Pythia\cite{Pythia} and ATLFAST II to describe the signal. The applied parameter settings are given in Appendix B. A large part of the samples described above in the context of the \( t \bar{t} \) analysis are considered as background in the analysis in Chapter 7 as well. Furthermore, \( W + \text{jet} \) samples without a jet filter come into play. The cross sections are listed in Table 3.2.

For the two \( W' \to tb \) samples, the mass of the \( W' \) boson is set to \( m_{W'} = 750 \text{ GeV} \) and \( m_{W'} = 1 \text{ TeV} \) respectively. Approximately \( 10^4 \) events are generated for each sample. The parameters describing the \( W' \) couplings to fermions are set equal to the Standard Model \( W \) boson couplings to fermions. Only events in which the top quark decays leptonically are generated. The predicted cross sections depend on the model in which the \( W' \) boson is introduced, two of which are listed here as benchmarks.

In case of the Littlest Higgs Model, the coupling of the \( W' \) boson to fermions is equivalent to that of the Standard model \( W \) boson when setting the mixing angle parameter \( \cot \psi \) equal to unity (cf. Section 1.3.1). The production cross section is proportional to \( \cot^2 \psi \) and decreases with increasing values of \( m_{W'} \). The values for the production cross section times branching ratio, i.e. \( \sigma(pp \to W') \times BR(W' \to tb) \), follow from Pythia.

The \( W' \to tb \) cross sections for the LRTH Model are evaluated with Calchep\cite{Calchep}, setting the proton PDFs to the CTEQ parametrization. More details on the parameters can be found in Appendix B.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \sigma(10 \text{ TeV}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W' \to tb \ (m_{W'} = 750 \text{ GeV}) )</td>
<td>4.34 pb \hspace{0.5cm} 1.35 pb</td>
</tr>
<tr>
<td>( W' \to tb \ (m_{W'} = 1 \text{ TeV}) )</td>
<td>1.39 pb \hspace{0.5cm} 0.26 pb</td>
</tr>
<tr>
<td>( W + \text{ jets (unfiltered)} )</td>
<td>( 48 \cdot 10^3 \text{ pb} )</td>
</tr>
</tbody>
</table>

Table 3.2: The cross sections for \( W' \to tb \) at \( \sqrt{s} = 10 \text{ TeV} \). The branching fraction for the leptonic decay of the Standard Model \( W \) boson is included.

Here, the interference of the \( W' \to tb \) diagram with the Standard Model single top \( s \)-channel diagram is neglected. This is motivated by the large mass difference between the Standard Model \( W \) boson and the \( W' \) boson, which results in an inevitable suppression of either of the propagators.

### 3.4 Detector Simulation

GEANT4\cite{GEANT4} is an extensive particle simulation toolkit that governs all aspects of the propagation of particles through detectors, based on a description of the geometry of the detector components and the magnetic field. The physics processes include ionization, Bremsstrahlung, photon conversions, multiple scattering, scintillation, absorption and transition radiation.

The detector is described in terms of almost 30 million volumes with properties, which in case of the ATLAS detector are constructed based on two databases: the geometry database.
and the conditions database. The former contains all basic constants, e.g. dimensions, positions and material properties of each volume. The latter is updated according to the circumstances at a given time and contains for instance dead channels, temperatures and misalignments. As a result, several layouts of the detector are available. Test beam data taken with components of the ATLAS detector before completion have aided the validation and further improvement of the detector simulation [33].

Due to the detailed and complicated geometry of the ATLAS detector and the diversity and complexity of the physics processes involved, the consumed computing time per event is large ($\mathcal{O}(1 \text{ hour})$). This has been a motivation for the development of "fast simulation" alternatives, which make use of parameterizations of the detector response. The standard GEANT4 simulation that exploits the full potential is referred to as "full simulation." The majority of the events studied in this thesis are produced with full simulation, with the exception of the $W' \rightarrow tb$ samples in the analysis in Chapter 7, which have been produced with ATLFAST II.

**ATLFAST II**

ATLFAST II [53] is a compromise between full and fast simulation; both the inner detector and the muon spectrometer are fully simulated with GEANT4, whereas the propagation of particles through the calorimeters is described by a parameterization [54]. This configuration is motivated by the fact that GEANT4 spends approximately 80% of its computing time on particles producing showers in the calorimeters.

After propagation through the inner detector, all remaining particles except muons are disregarded. The muons are further propagated in the full detector simulation to produce the energy deposits in the calorimeters as well as the hits in the muon spectrometer. The absent electromagnetic and hadronic showers in the calorimeters from the disregarded particles are estimated by a parameterization which is obtained from a fully simulated sample of single photons and single charged pions. To assess the parameterization, the energies of the generated particles vary from 0.2 to 500 GeV and their directions are evenly distributed in $|\eta| < 5$ and $-\pi < \varphi < \pi$. The particle showers are described by two parameterizations: one corresponding to the total energy deposit in each calorimeter layer and another describing the energy distribution over the cells within a layer. The latter, the "shape" parametrization, is based on the assumption that the energy distribution perpendicular to the direction of flight is radially symmetric. In ATLFAST II, the calorimeter particle showers of electrons and photons is approximated by the photon parameterization and all hadrons are described by the pion parameterization. The consumed computing time per event proves to decrease with a factor of 20 compared to full simulation [55]. Concerning physics performance, the agreement is at the percent level.