

**Arbeit zur Erlangung des akademischen Grades
Bachelor of Science**

**Search for single top-quark production
in the s-channel with the ATLAS
experiment**

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Kurzfassung

In dieser Arbeit werden Studien zur Messung des Wirkungsquerschnitts für die Erzeugung einzelner Top-Quarks im s-Kanal bei Proton-Proton Kollisionen mit einer Schwerpunktsenergie von $\sqrt{s} = 13 \text{ TeV}$ durchgeführt. Die Daten stammen aus Kollisionsexperimenten des LHC und wurden vom ATLAS Detektor in den Jahren 2015 bis 2018 aufgenommen. Zur Extrahierung des Wirkungsquerschnitts wird ein Profile Likelihood Fit verwendet, wobei als Diskriminante die Ergebnisse eines *Deep Neural Networks*(DNN) fungieren. Die Signal Signatur besteht aus einem geladenen Lepton, entweder Elektron oder Myon, zwei b-tagged Jets und fehlendem transversalen Impuls.

Was mache ich denn eigentlich genau in meiner Arbeit? Was könnte ich noch dazu schreiben?

- Run 2 Daten
- integrierte Luminosität
- Wie funktioniert die DNN? Es nutzt high-level kinematic variables. Was ist das überhaupt?
- Mache deutlicher dass ich simulierte Daten verwende
- Erkenntnisse aus dem Resultat vielleicht hier noch mit rein schreiben?
- Welche Uncertainties behindern uns am meisten? Background modelling, signal modelling, detector modelling
- kleiner Wirkungsquerschnitt des s-kanals und großer hintergrund bei ähnlichen signaturen
- s kanal bis jetzt nicht präzise gemessen, andere single top channel schon präzise genug gemessen
- Machen wir einen Asimov Fit? Was ist das genau?

Abstract

The abstract is a short summary of the thesis in English, together with the German summary it has to fit on this page.

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1 Introduction

The Standard Model (SM) of particle physics is the best descriptor for the behaviour of elementary particles and the interactions between them. Despite its major successes, like the discovery of the Higgs boson (citation) or the top quark(citation), many phenomena remain unexplained. Physics beyond the Standard Model (BSM) is needed to make breakthroughs in dark matter, neutrino oscillations or the matter-antimatter disbalance.

As the heaviest fermion with a mass of about 172.5 GeV (citation?), the top quark is the strongest coupler with the Higgs field and may act as a potential probe for electroweak symmetry breaking. Therefore in it lies potential in uncovering BSM physics. The challenge lies in its short lifetime of 5×10^{-25} s (citation), which makes hadronisation impossible and almost exclusively leads to a W -boson and a bottom-quark as decay products.

At the ATLAS experiment of the Large Hadron Collider (LHC) top-quarks predominantly come in pairs of $t\bar{t}$ via the strong interaction. Although, top quarks can be produced singly via the electroweak interaction, with the single-top production in the s- and t-channel, as well as in tW associated production. The s-channel has the smallest cross section of 10.32 pb of all mentioned processes and is dominated heavily by background processes. Unlike the other single modes, the s-channel has not yet been measured precisely with a significance over 5σ , with the latest ATLAS measurement achieving an observed (expected) significance of 3.3(3.9). Even with its small cross section, the major hindrance in the measurement is the systematic uncertainties. To get a better measurement, this thesis will use a more modern approach, with a DNN output as the discriminant for a profile likelihood fit. Simulated data from proton-proton collisions in the LHC at $\sqrt{s} = 13$ TeV corresponding to the full Run 2 dataset with a luminosity of 140 fb^{-1} from the ATLAS detector is used.

The structure of this work constitutes the following content. In chapter 2 an overview of the SM, the s-channel production mode as well as the dominant backgrounds and the previous measurement is given. Chapter 3 presents the ATLAS detector. Chapter 4 lists the samples, the object definitions and event selections used. Chapter 5 describes the main study presented in this thesis. Finally chapter 6 gives a short

1 Introduction

summary of the results and an outlook for further advances in the measurement of the single top s-channel.

2 Properties of the Top Quark within the Standard Model

2.1 Overview of the Standard Model

The SM of particle physics is a gauge invariant theory, which describes the fundamental particles and the interactions between them. It was developed throughout the 20th century (citation) by combining the discoveries of quantum mechanics and special relativity into a quantum field theory. Three of the four fundamental forces, electromagnetism, the strong interaction and the weak interaction are characterized by it, only excluding gravity. Whereas electromagnetism and gravity act on infinite ranges, the strong and weak force act on subatomic scales.

The SM divides the fundamental particles into two main categories. First fermions, which constitute all known matter and carry half integer spin. Second bosons, which act out the interactions between fermions and carry a whole integer spin. Further, bosons can be divided into vector bosons, with spin 1 and a scalar boson, the Higgs boson (H) with spin 0. The fermions are comprised of quarks and leptons, where both interact with the electromagnetic (EM) force but only quarks experience the strong force. Neutrinos, which take part in the lepton category, only interact via the weak force. The fundamental particles are further split into three generations in relation to their masses and time of discovery. The first generation is comprised of the electron (e) and the corresponding electron neutrino (ν_e) for the lepton part, and the up quark (u) as well as the down quark (d). The second generation leptons include the muon (μ) and the muon neutrino (ν), while the charm quark (c) and the strange quark (s) constitute the second generation quarks. The third generation includes the heaviest fermions, with the tau lepton (τ) and its corresponding tau neutrino (ν_{tau}) on the lepton side and the top quark (t) and bottom quark (b) on the quark side. The electric charge defines the interaction strength with the EM force. All charged leptons posses an electric charge of -1 elementary charge (e). Whereas up-type quarks (u, c, t) carry a charge of $+2/3 e$ and down-type quarks (d, s, b) carry a charge of $-1/3 e$. For every fermion there exists an antiparticle counterpart with opposite electric charge and spin. Especially the first generation of fermions constitute to the overwhelming part of matter, where protons and neutrons are build with the u - and d -quarks and electrons as part of atoms.

2 Properties of the Top Quark within the Standard Model

The force carrying bosons include the photon (γ) for the EM interaction, the W^\pm and Z bosons for the weak interaction and eight gluons with different colour for the strong interaction. The photon is mass- and chargeless, with it coupling to every particle possessing an electric charge. The W^\pm and Z bosons of the weak interaction carry relatively high mass, which is the reason for its narrow interaction range. The weak force acts on every fermion, where the W^\pm bosons couple to the weak isospin and the Z boson couples to the weak hypercharge, a combined value of the electric charge and weak isospin. Gluons, mediating the strong interaction, are massless as well and couple to any particle carrying a colour charge, either quarks or gluons themselves. There are the three base colours red, green and blue with a respective anticolour counterpart. Gluons always carry two colour charges, one base colour and one anticolour, resulting in eight different possible permutations. Quarks carry only one colour charge. Colour confinement states that every stable composite particle has to be colorless, which is the reason for the finite range of the strong interaction. These stable composites are called hadrons and are further split into mesons and baryons. Mesons are colour neutral quark-antiquark pairs. Baryons are colour neutral composites of three quarks. The Higgs Boson, proposed by Peter Higgs in 1964 [higgs], was discovered in 2012 in a combined effort of the ATLAS [atlas_higgs] and CMS [cms_higgs] experiment at the LHC. As a scalar boson it carries spin 0, no electric charge and is the heaviest boson ($m_H = (125.20 \pm 0.11)$ GeV [higgs_mass]). It mediates none of the fundamental forces, but by coupling to it fermions and the W^\pm and Z boson gain their mass.

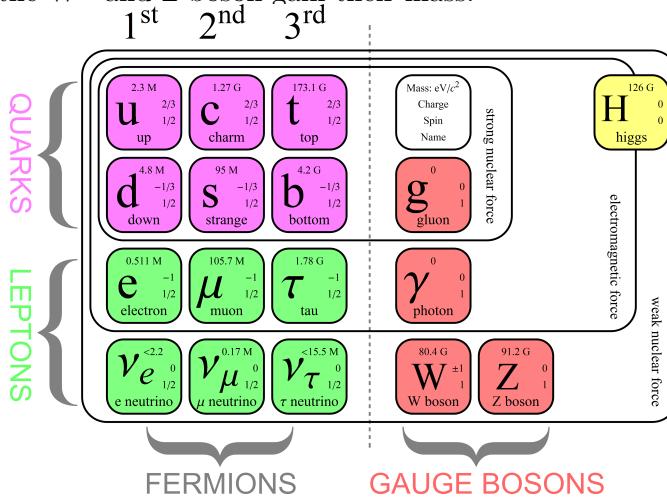


Figure 2.1: The fundamental particles of the Standard Model, showing which forces act on them respectively [2]

2.2 The Top Quark

First postulated by Makoto Kobayashi and Toshihide Maskawa in 1973 and later discovered at Fermilab with the CDF and DØ experiments of the Tevatron collider in 1995 in $p\bar{p}$ collisions, the top quark is the last discovered quark in the SM. As up-type quark in the third generation, it carries the heaviest mass of all quarks at $m_t = (172.53 \pm 0.29) \text{ GeV}$ (citation), it possesses a large decay width of $\Gamma_t = 1.42^{+0.19}_{-0.15} \text{ GeV}$ (citation). A large decay width leads to a short mean life time of $\tau = \hbar/\Gamma_t \approx 5 \times 10^{-25} \text{ s}$. Unlike other quarks, which hadronise due to colour confinement, the top quark decays before hadronisation is possible, due to its short lifetime. The top's properties, like spin information or kinetic properties, are then to be decoded by studying the decay particles, which makes its analysis especially interesting. The top quark decays almost exclusively into a W-boson and a b -quark.

2.2.1 Single top-quark production in the s-channel

The s-channel is one of the electroweak single top-production modes. In the single top-quark s-channel, a top-quark and a bottom antiquark are created from a virtual W-boson, after the annihilation of a quark and antiquark. The s-channel shows a tWb vertex, where the CKM matrix element $V_{tb} \approx 1$ is involved. Therefore the s-channel is a strong probe for the electroweak properties of the top quark. In the LHC, the annihilating particles are predominantly valence up quarks (u) and antidown (\bar{d}) from the pool of sea quarks in the colliding protons. The Feynman diagram of the s -channel process at LO is shown in Figure 2.2a.

The parton density function (PDF) is a representation of the probability distribution with which a parton carries a fraction of the momentum of a hadron, denoted by using the *Bjorken* x . $p_i = xp_p$ resembles the momentum fraction the parton i carries from the whole proton momentum p_p . Where a parton is a hadron component, either a quark or gluon. The cross-section $\sigma_{s-\text{chan.}}$ of the single top quark s -channel process, is determined using the factorisation theorem of the QCD. By convolving the PDFs of the parton constituents i and j with the cross section $\sigma_{ij \rightarrow t\bar{b}}$ of the respective sub-process and then summing over all possible sub-processes, the s -channel cross section is determined.

$$\sigma_{s-\text{chan.}} = \sum_{i,j} \int dx_i f_i(x_i, \mu_F^2) \int dx_j f_j(x_j, \mu_F^2) \sigma_{ij \rightarrow t\bar{b}}(\sqrt{s}, m_t, \mu_F, \mu_R, \alpha_S).$$

The formular takes in, the centre-of-mass energy \sqrt{s} of the process, the top quark mass m_t , the coupling strength of the strong interaction α_S , as well as the factorisation scale μ_F and the renormalisation scale μ_R , which are set to the energy scale of the process.

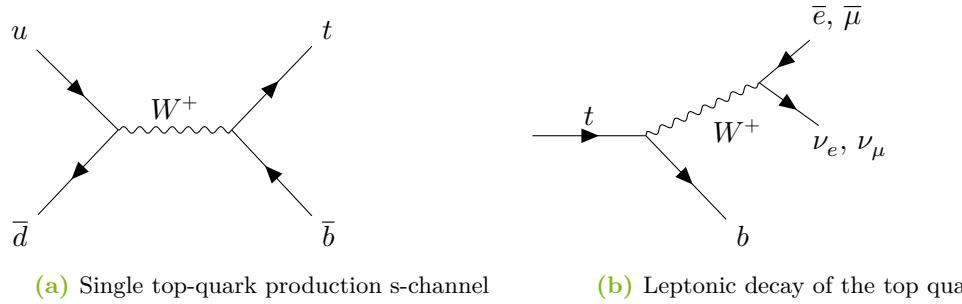


Figure 2.2: Feynman Diagram of the singlte top-quark s-channel production mode and further decay of the top-quark.

2.2.2 Top quark decay

The top quarks decay occurs via the weak interaction, hinted by the resulting decay products consisting of a b -quark and a W -boson. Furhter, the W -boson decays either hadronically $2/3$ or leptonically $1/3$ of the times. Hadronic decay results into quark pairs, wheresas the leptonic decay emits a lepton and its corresponding neutrino. As there are different color permutations the quarks can carry, the phase space for the hadronic decay is larger, making it more likely than the leptonic decay. During the s-channel analysis only leptonic W -boson decays are selected, as the resulting jets from the hadronic decay are contaminated by multijet background. Since neutrinos cannot be directly detected, the event has to be examined for missing transverse momentum E_T^{miss} . If the sum of all transverse momenta of all the outgoing particles, does not add to zero, then a particle has remained undetected and the event has missing transverse momentum E_T^{miss} , as prior to the pp collision both beam momenta should cancel out. The leptonic decay mode of the top quark, as looked for in this thesis, is shown in Figure 2.2b.

The searched for signature consist therefore of a charged lepton from the leptonic W -boson decay, missing transverse momentum E_T^{miss} from the undetectable neutrino, and two b-tagged jets, one produced from the \bar{b} -quark of the s-channel process itself and one from the b -quark of the top-quark decay. τ leptons have a short lifetime and can thus not be detected, but first and second generation leptons from the τ

decay can be observed. Because of that lepton signature is narrowed down to either an electron or muon.

2.2.3 Background Processes

There are processes with similar signatures in the detector. Differentiating these processes from the signal process of interest is a major task in any analysis. These so called background processes consist predominantly of $t\bar{t}$ production and W+jets production for the single top s-channel analysis. In the LHC experiment $t\bar{t}$ production occurs mostly through gluon-gluon fusion, but with less probability can also happen through quark-pair-annihilation. With a theoretical cross-section of $\sigma_{t\bar{t}}^{\text{Theo.}} = 832^{+20}_{-29} \text{ pb}$, it exceeds every other top quark production mode. The other single top quark production modes can be mistaken for signal as well, but to a lesser degree, since their cross sections are noticeably smaller than $t\bar{t}$ with $\sigma_{t\text{-chan.}}^{\text{Theo.}} = 216.99^{+9.04}_{-7.71} \text{ pb}$ and $\sigma_{tW\text{-Prod.}}^{\text{Theo.}} = (71.7 \pm 3.8) \text{ pb}$. Other minor backgrounds stem from multijet background processes, Z+jets or diboson(WW,WZ,ZZ) production. Figure 2.3 shows the LO Feynman diagrams for $t\bar{t}$ production via gluon-gluon fusion in the s-channel, and the other two single top-quark production modes.

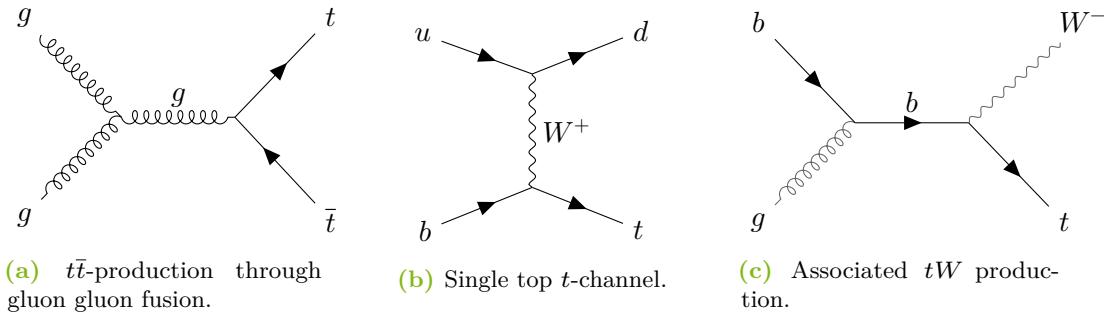


Figure 2.3: Feynman diagrams at LO for the major background processes in the analysis of the single top quark s-channel production mode.

Not only does the $t\bar{t}$ -production mode hold a high cross-section, but the fact that it produces real top-quark decays makes it a difficult background. The two W -bosons, resulting from the t -quark and \bar{t} -quark decay, again can decay leptonically or hadronically. If both W -bosons decay leptonically, the dileptonic final state, can mimic the signal signature if one of the leptons stays undetected. For the semileptonic decay, where one W -boson decays leptonically and one hadronically, the final state signature can emulate the signal if only two b-tagged jets get detected. The fully hadronic decay is very unlikely to be mistaken for the signal. Likewise the

single top-quark production mode in the t -channel and the associated tW production show real top quark decays in their signatures. For the t -channel the final state reproduces the signal signature if a b-tagged jet or misidentified lighter quark jet gets associated with the event. In the associated tW -production, the b -quark turns into a t -quark by emitting a W -boson. If this W -boson decays hadronically and produces a b-tagged jet or a jet that gets misidentified, the final state signature is the same as the signal signature. Provided, the W -boson decays leptonically and two b-tagged jets or misidentified jets get associated with the event, the $W+jets$ background mimics the signal. And in the case of multijet background, leptons from heavy flavor decays, electrons from photon conversion or jets misidentified as leptons paired with two associated b-tagged jets or misidentified jets lead to the signal signature.

2.2.4 Previous measurement

- Beschreibe welche Unsicherheiten genau die vorherige Messung verschlechtert

In Figure 2.4 previous measurements of the three different single top-quark production modes at different center of mass energies \sqrt{s} are shown, taken at the ATLAS and CMS experiments at the LHC with data from pp -collisions.

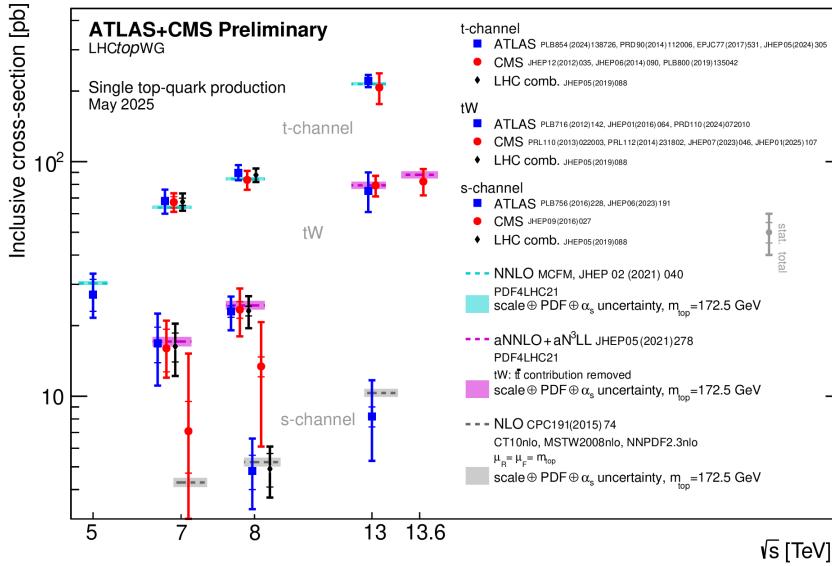


Figure 2.4: Chart of all measurements taken of the three different single top production modes at the ATLAS and CMS experiments [prev_measure]

The most recent measurement of the s-channel was done by ATLAS with a center of mass energy of $\sqrt{s} = 13$ TeV, with data collected between the years 2015 and 2018, corresponding to the Run 2 dataset at an integrated luminosity of 140 fb^{-1} . The cross section of the measured s-channel resulted in $\sigma_{\text{s-chan}} = 8.2 \pm 0.6(\text{stat.})^{+3.4}_{-2.8}(\text{syst.}) \text{ pb}$, in comparison to the theoretical estimate of $\sigma_{\text{s-chan}}^{\text{theo.}} = 10.32^{+0.40}_{-0.36} \text{ pb}$. This is equivalent with an observed (expected) signal significance over the background only hypothesis of $3.3(3.9)\sigma$. The analysis strategy consisted of a preselection and then a split into one signal region and three validation regions, for better modelling of the background processes. To extract the signal strength from the events, a profile likelihood fit was done, with a matrix element method (MEM) discriminant. The limiting factors of the previous measurement were noticeably the systematic uncertainties.

3 The ATLAS detector

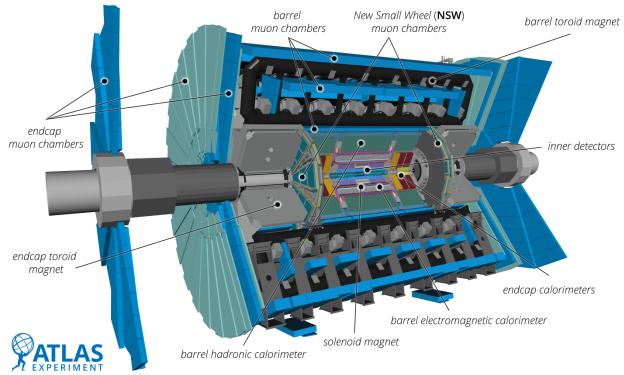


Figure 3.1: Schematic overview of the ATLAS Detector and all its subsystems [1]

As a general purpose detector, the ATLAS detector covers a solid angle range of 4π . The full angular coverage in the beams symmetry plane is granted through its cylindrical design, with a central barrel and two endcaps. It consists of three main subsystems, which are the *Inner Detector* (ID), the *Calorimeter System* and the *Muon Spectrometer* (MS). With the help of a 2 T solenoid magnet, the trajectory of charged particles are bent using the Lorentz force and then reconstructed inside the ID. The calorimeter system consists of an Electromagnetic Calorimeter (ECAL) and Hadronic Calorimeter (HCAL). Inside the ECAL the incoming electrons and photons trigger showers, which ionize parts of the calorimeter and results in energy and direction measurements. Similarly, the HCAL absorbs hadronic jets and triggers hadronic showers, leading to light emissions in the scintillator tubes of the HCAL, from which energy and direction of the jets are determined. As minimal ionizing particles, muons pass all the previously mentioned subsystems and can only be detected in the MS. Here the toroidal magnets in the endcap and barrel parts of the detector bend their tracks and helps in trajectory and charge measurements.

Cartesian coordinates within the LHC are defined as follows: The z -axis is aligned with the beam pipe, the x -axis points to the center of the LHC and the y -axis points upwards to the beam plane. To introduce spherical coordinates, ϕ is used to describe the angle between the y - and x -axis, while θ describes the angle between the y - and z -axis. Lorentz invariance can then be achieved by introducing the pseudorapidity

$\eta = -\ln(\tan \frac{\theta}{2})$. Particle distances within the detector are then defined by the value $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. Transverse momentum is calculated within the cartesian coordinates with $p_T = \sqrt{p_x^2 + p_y^2}$.

4 Object Definition and Event Selection

4.1 Monte Carlo Samples

In order to study processes in particle physics, signal processes have to be separated from background processes. Instead of only using recorded data, simulations are done, to better compare these processes with their SM predictions, via varying assumptions and parameters. In this thesis the single top-quark s -channel production mode is to be examined, with the major backgrounds being $t\bar{t}$ -production, single top-quark production in the t -channel, associated tW -production, W +jets and Z +jets production.

- Wie gehen wir mir Multijet Background um?

Monte Carlo (MC) simulators are used to reproduce particle events using a Markov Chain process. At LO and NLO, hard scattering events can be calculated using perturbation theory, by calculating the relevant matrix elements (ME). Whereas parton showers (PS) and hadronization due to the strong interaction have to be calculated, utilizing phenomenological models to incorporate the effects of confinement and asymptotic freedom present in QCD. These models use different hadronization models and free parameter, which are tuned using recorded data. As a general purpose MC simulator SHERPA can calculate the hard scattering ME, as well as parton showers and hadronisation. POWHEG BOX v2 can generate hard scattering events up to NLO. PYTHIA 8 models parton shower and hadronisation via the *Lund String model*, typically making use of the *A14* tune. HERWIG 7 calculates parton showers and hadronisation via the *heavy cluster model*. Finally, EVTGEN simulates the decay heavy-flavour hadrons, especially b and c hadrons. During all simulations a top-quark mass of 172.5 GeV is utilized.

For the nominal single top-quark and antitop-quark s -channel samples, POWHEG simulations combined with PYTHIA are used under the *A14* tune. Heavy-flavour decays are further calculated by EVTGEN.

The t -channel single top-quark and anti-quark processes similarly make use POWHEG and PYTHIA. The leptonic decay of the W -boson from the top-quark decay is enforced and a Breit-Wigner propagator scheme with a fixed top-quark width of 50 GeV is used (Was ist das genau?).

Associated tW production samples are generated with POWHEG interfaced with PYTHIA, while further making use of the diagram removal scheme (citation) to handle interference with $t\bar{t}$ production at NLO. The NNPDF3.0NLO PDF set is used in HERWIG for these samples.

The $t\bar{t}$ production is both simulated with the full-sim and fast-sim detector model, while utilizing the POWHEG generator at NLO with the NNPDF3.0NLO PDF set, combined with PYTHIA. The h_{damp} parameter, which regulates the first gluon emission beyond the Born configuration (Was ist das?), is set to $1.5 \cdot m_{\text{top}} \simeq 258.75 \text{ GeV}$.

For the $W+\text{jets}$ samples the SHERPA 2.2.11 version is used, instead of SHERPA 2.2.14. Here SHERPA calculates the matrix elements at NLO accuracy for up to two partons and at LO accuracy for up to five partons, which is combined with parton shower models.

The Drell-Yan (was ist das?) production modes of $Z \rightarrow ee$, $Z \rightarrow \mu\mu$, $Z \rightarrow \tau\tau$ are simulated with SHERPA 2.2.11 for the light leptons. For tau decay SHERPA 2.2.14 with the NNPDF3.0NNLO PDF set is utilized. Samples inside different invariant-mass regions, involving a low-mass interval of ($10 < m_{ll} < 40 \text{ GeV}$), is used to improve description of dilepton spectra.

4.2 Systematic Samples

4.3 Object Definition

The signal signature consist of different objects of significance: leptons, either electrons or muons, and their corresponding neutrinos, as well as hadron jets, especially important b-tagged jets. To reconstruct these objects from the detector response a framework for the respective object definitions is to be used.

Electrons are reconstructed from particle tracks in the ID and energy deposits in the ECAL. A measured $p_T > 10 \text{ GeV}$ and $|\eta_{\text{cluster}}| < 2.47$, while deposits in the barrel-end cap transition region $1.36 < |\eta_{\text{cluster}}| < 1.52$ are discarded, are necessary, as well as passing the TightLH and isolation working point, for an electron to be identified as such. Muons require at least a $p_T > 10 \text{ GeV}$ and $|\eta| < 2.5$, while passing the medium quality definition and tight isolation working point. Jets are reconstructed with the anti- k_t algorithm with a radius parameter of $\Delta R = 0.4$. The GN2v01 algorithm, determines if a jet is to be determined as b-tagged.

4.4 Event Selection

	SR
$n(e, \mu)$	$\equiv 1$ with $p_T > 30 \text{ GeV}$
$n(\text{jets})$	$\equiv 2$, in $ \eta < 2.5$
$n(b - \text{tags})$	$\equiv 2$, @77%, in $ \eta < 2.5$
Leading jet p_T	$> 40 \text{ GeV}$, in $ \eta < 2.5$
Subleading jet p_T	$> 30 \text{ GeV}$, in $ \eta < 2.5$
Missing transverse energy (E_T^{miss})	$> 35 \text{ GeV}$
Transverse W boson mass	$> 30 \text{ GeV}$
Additional jets (low p_T) veto	No jets with $p_T < 30 \text{ GeV}$
Forward jets veto	No jets with $ \eta > 2.5$
Additional leptons veto	No extra leptons with $p_T < 30 \text{ GeV}$

- Include table with event yields

5 main study and results

5.1 Analysis strategy

- wirkungsquerschnitt über signal region
- ME method schwierig bei kleinem B/S
-
- Discriminant variable is DNN
- Profile likelihood fit hier erwähnen

5.2 DNN Model variables

- Fullsim and fastsim(more statistics) used for training

5.3 Separation power

-

5.4 profile likelihood fit

-

5.5 systematic uncertainties

-

6 Summary and outlook

- keine control regions
- fake estimate
- anderer b-tagging working point
- welche systematics nochmal besser anschauen

A Ein Anhangskapitel

Hier könnte ein Anhang stehen, falls Sie z. B. Code, Konstruktionszeichnungen oder Ähnliches mit in die Arbeit bringen wollen. Im Normalfall stehen jedoch alle Ihre Resultate im Hauptteil der Bachelorarbeit und ein Anhang ist überflüssig.

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- [2] Nicola Serra. *Standard Model*. 2025. URL: <https://www.physik.uzh.ch/groups/serra/StandardModel.html>.

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