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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. Eine Vielzahl an von kinematischen Variablen wird hinsichtlich ihrer Trennkraft zwischen Signal und Untergrund untersucht.

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.

Contents

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, 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, which makes hadronisation impossible and almost exclusively leads to a W-boson an 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 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 $+{}^{2}\!/_{3}\,\mathrm{e}$ and down-type quarks (d, s, b) carry a charge of $-{}^{1}\!/_{3}\,\mathrm{e}$. For every fermion there exists an antiparticle counterpart with oppsite 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.

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 possesing 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 glouns 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-anitquark 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 ($m_{\mathrm{H}} = (125.20 \pm 0.11)$ 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.

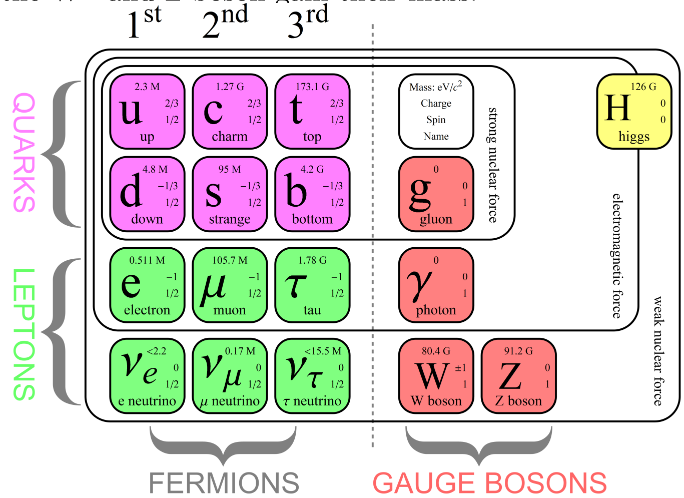

Figure 2.1: The fundamental particles of the Standard Model, showing which forces act on them respectively [1]

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 $p\overline{p}$ 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 $m_\mathrm{t} = (172.53 \pm 0.29)$ GeV (citation), it posseses a large decay width of $\Gamma_t = 1.42^{+0.19}_{-0.15}$ GeV (citation). A large decay width leads to a short mean life time of $\tau = \hbar/\Gamma_\mathrm{t} \approx 5\times10^{-25}$ s. Unlike other quarks, which hadronise due to colour confinement, the top quark decays befor hadronisation is possible, due to its short lifetime. The tops 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

- s-channel is our production mode of interest
- tt bar via gluon gluon fusion is predominiant mode
- s-channel has the smallest cross section
- Anti quarks from sea quarks in the pdf
- Explain PDFs to explain sea and partons
- How does the theoretical cross section get calculated? Via factorisation theorem
- s-channel feynman diagram

2.2.2 Top quark decay

- decay via weak interaction
- decay into W boson and bottom quark because of CKM $V_t b$ approx 1
- W boson can decay hadronically 2/3 or leptonically 1/3. Hadronic channel has bigger phase space because of more color charge possibilities
- dileptonic, semileptonic or hadronic challenge
- hadronic decay can be detected through jets

- leptonic decay leads to undetected neutrino. This leads to E_t^{miss}(how is it calculated?)
- What do the different channel signatures look like?
- We use semileptonic channel because of multijet background

2.2.3 Background Processes

Hier kann ich im Prinzip alles aus der Präsi rein hauen

- What is background (Processes with similar signature)
- What are the most relevant backgrounds
- Feynman diagramms of background
- erklären wann background als signature gesehen werden kann
- Also im Prinzip präsi. Bei Noah steht nicht viel

2.2.4 Previous measurement

- Diagramm der vorherigen sinlge top measurements rein
- Wichtigsten Stichpunkte ur vorherigen messung
- measured cross section
- measured (expected) significance
- which data at which lumi

In Figure 2.2 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.

The most recent measurement of the s-channel was done by ATLAS with a center of mass energy of $\sqrt{s} = 13\,\text{TeV}$, with data collected between the years 2015 and 2018, corresponding to the Run 2 dataset at an integrated luminosity of $140\,\text{fb}^{-1}$. 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 $\sigma^{\text{theo.}}_{\text{s-chan}} = 10.32^{+0.40}_{-0.36}\,\text{pb}$. 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

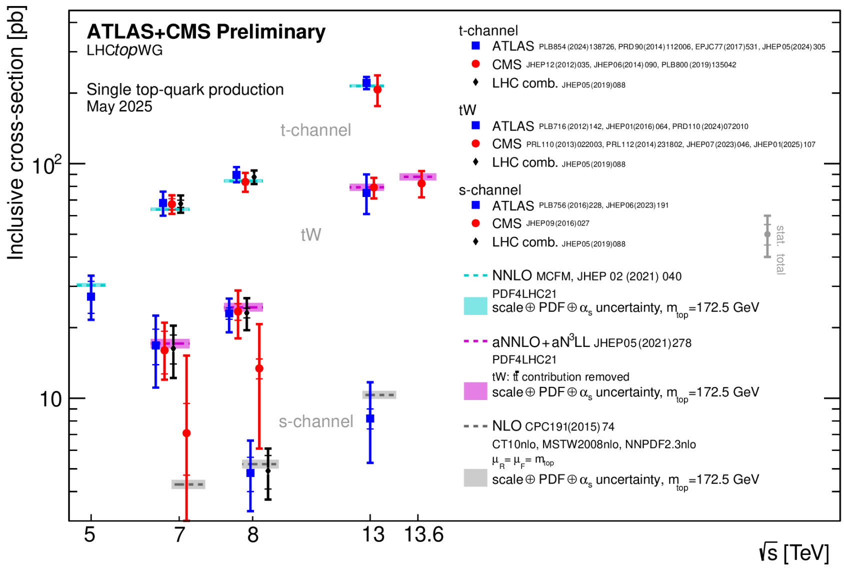

Figure 2.2: Chart of all measurements taken of the three different sinlge top production modes at the ATLAS and CMS experiments [**prev_measure**]

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 where noticeably the systematic uncertainties.

3 detector

4 objet definition and event selection

5 main study and results

6 Summary and outlook

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.

Bibliography

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

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