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Improvement of the single top-quark detection in the s-channel at the CMS Experiment

Genti Saliu

Department of Physics
Karlsruhe Institute of Technology (KIT)

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Reviewer: Prof. Dr. Thomas Müller
Second reviewer: Dr. Nils Faltermann

Institute of Experimental Particle Physics

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(**Prof. Dr. Thomas Müller**)

I hereby certify that the enclosed thesis is my own work, that I have not sought or used inadmissible help of third parties to produce this work and that I have clearly referenced all sources used in the text.

Karlsruhe, XX MONTH 2018

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(**Genti Saliu**)

Abstract

Contents

1 Theoretical Background

This chapter discusses the relevant theory for the thesis. Section 1.1 provides a condensed overview of the experimental aspect of the standard model (SM) of particle physics, the framework for this work. Section 1.2 focuses on properties of the top quark, its production processes and decay modes, which will be relevant for the development and evaluation of the classifier in chapters 3 and 3.

1.1 The Standard Model of Particle Physics

The SM describes the known elementary particles and their interactions. Elementary particles are grouped into fermions and bosons based on their spin quantum number.

Fermions are particles with a spin of $1/2$. They are grouped into six quarks and six leptons, which are arranged according to their masses in three generations. The quarks are the up (u), down (d), charm (c), strange (s), top (t) and bottom (b) quark. The leptons consist of the electron (e), electron neutrino (ν_e), muon (μ), muon neutrino (ν_μ), tau (τ), tau neutrino (ν_τ). For each fermion an antifermion with same mass, but opposite electric charge, color and third component of isospin, exists. A summary of the fermions is given in table 1.1.

Table 1.1: Fermions of the standard model. Source: [2, 3]

Fermions	Generation 1	Generation 2	Generation 3	Electric charge	Color	3rd component of isospin I_3	Spin
Leptons	ν_e	ν_μ	ν_τ	0	—	$+1/2$	$1/2$
	e	μ	τ	-1		$-1/2$	
Quarks	u	c	t	$+2/3$	r, b, g	$+1/2$	$1/2$
	d	s	b	$-1/3$		$-1/2$	

Quarks carry color charge, electric charge and weak isospin - they interact with other quarks via the strong, electromagnetic and weak interaction respectively. A quark's color can take one of three charges (red, green, and blue), an antiquark one of the three anticolors (antired, antigreen, and antiblue). Due to color confinement, quarks cannot be isolated, they are strongly bound to one another forming color-neutral composite

particles (hadrons). Hadrons consist of mesons (one quark, one antiquark) and baryons (three quarks), such as the proton (uud) and the neutron (udd). Quarks from the same generation form a weak isospin doublet; particles from the same doublet behave similarly towards the weak interaction.
Leptons do not possess color charge. The three neutrinos lack additionally in electric charge and only interact through the weak nuclear force, thus being difficult to detect. The electron, muon, and tau have electric charge and interact electromagnetically.
First-generation charged particles do not decay, they constitute ordinary matter. Neutrinos do not decay either, they exist in abundance, but do not interact with matter. Other higher generation charged particles have very short lifetimes and can be observed in high-energy experiments only [5].

The interactions of the SM are described by quantum field theories [4]:

- The electromagnetic interaction is described by quantum electrodynamics (QED), wherein the photon (γ) acts as the force carrier that mediates the interaction between electrically charged particles. Because photons are not electrically charged, they do not interact with other photons.
- The strong interaction is described by quantum chromodynamics (QCD).
- The weak interaction

Gauge **bosons** are defined as force carriers that mediate the strong, weak, and electromagnetic fundamental interactions. With the exception of the Higgs boson, which has spin 0, bosons have spin 1, follow Bose-Einstein statistics and do not obey the Pauli exclusion principle.

Interactions in physics are the ways that particles influence other particles. At a macroscopic level, electromagnetism allows particles to interact with one another via electric and magnetic fields, and gravitation allows particles with mass to attract one another in accordance with Einstein's theory of general relativity. The Standard Model explains such forces as resulting from matter particles exchanging other particles, generally referred to as force mediating particles. When a force-mediating particle is exchanged, at a macroscopic level the effect is equivalent to a force influencing both of them, and the particle is therefore said to have mediated (i.e., been the agent of) that force. The Feynman diagram calculations, which are a graphical representation of the perturbation theory approximation, invoke "force mediating particles", and when applied to analyze high-energy scattering experiments are in reasonable agreement with the data. However, perturbation theory (and with it the concept of a "force-mediating particle") fails in other situations. These include low-energy quantum chromodynamics, bound states, and solitons. The gauge bosons of the Standard Model all have spin (as do matter particles). The value of the spin is 1, making them bosons. As a result, they

Table 1.2: The bosons of the standard model. Source: [2], [1]

Interaction	Acts on	Force carrier	Mass (GeV)	J^P	Range (m)
strong	color charge	8 gluons (g)	0	1^-	$\approx 10^{-15}$
electromagnetic	electric charge	Photon (γ)	0	1^-	10^{-15}
weak	weak charge	$W^{\pm}$	80.385	1	∞
		Z^0	91.188		

do not follow the Pauli exclusion principle that constrains fermions: thus bosons (e.g. photons) do not have a theoretical limit on their spatial density (number per volume). The different types of gauge bosons are described below.

These gauge bosons are the eight gluons, which mediate

Photons mediate the electromagnetic force between electrically charged particles. The photon is massless and is well-described by the theory of quantum electrodynamics. The W+, W-, and Z gauge bosons mediate the weak interactions between particles of different flavors (all quarks and leptons). They are massive, with the Z being more massive than the $W^{\pm}$. The weak interactions involving the W± exclusively act on left-handed particles and right-handed antiparticles. Furthermore, the $W^{\pm}$ carries an electric charge of +1 and -1 and couples to the electromagnetic interaction. The electrically neutral Z boson interacts with both left-handed particles and antiparticles. These three gauge bosons along with the photons are grouped together, as collectively mediating the electroweak interaction. The eight gluons mediate the strong interactions between color charged particles (the quarks). Gluons are massless. The eightfold multiplicity of gluons is labeled by a combination of color and anticolor charge. Because the gluons have an effective color charge, they can also interact among themselves. The gluons and their interactions are described by the theory of quantum chromodynamics. The interactions between all the particles described by the Standard Model are summarized by the diagrams on the right of this section.

The Higgs particle is a massive scalar elementary particle theorized by Peter Higgs in 1964, when he showed that Goldstone's 1962 theorem (generic continuous symmetry, which is spontaneously broken) provides a third polarisation of a massive vector field. Hence, Goldstone's original scalar doublet, the massive spin-zero particle, was proposed as the Higgs boson. (see 1964 PRL symmetry breaking papers) and is a key building block in the Standard Model. It has no intrinsic spin, and for that reason is classified as a boson (like the gauge bosons, which have integer spin).

The Higgs boson plays a unique role in the Standard Model, by explaining why the other elementary particles, except the photon and gluon, are massive. In particular, the Higgs boson explains why the photon has no mass, while the W and Z bosons are very heavy. Elementary-particle masses, and the differences between electromagnetism (mediated by the photon) and the weak force (mediated by the W and Z bosons), are critical to many aspects of the structure of microscopic (and hence macroscopic) matter. In electroweak theory, the Higgs boson generates the masses of the leptons (electron, muon, and tau) and quarks. As the Higgs boson is massive, it must interact with itself.

Because the Higgs boson is a very massive particle and also decays almost immediately when created, only a very high-energy particle accelerator can observe and record it. Experiments to confirm and determine the nature of the Higgs boson using the Large Hadron Collider (LHC) at CERN began in early 2010 and were performed at Fermilab's Tevatron until its closure in late 2011. Mathematical consistency of the Standard Model requires that any mechanism capable of generating the masses of elementary particles becomes visible at energies above 1.4 TeV; therefore, the LHC (designed to collide two 7 TeV proton beams) was built to answer the question of whether the Higgs boson actually exists.

On 4 July 2012, two of the experiments at the LHC (ATLAS and CMS) both reported independently that they found a new particle with a mass of about 125 GeV/c2, which is "consistent with the Higgs boson". It was later confirmed to be the searched-for Higgs boson.

1.2 The Top Quark

2 Experimental Background

2.1 The Large Hadron Collider

2.2 The Compact Muon Solenoid Experiment

3 NN-Classifier for Top-Quark Reconstruction

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Bibliography

[1] Nils Faltermann. *Single Top Quark Production at 13 TeV with the CMS Experiment: from Rediscovery to Search for Rare Channels and Determination of Higgs Boson Couplings*. Ph.D. thesis. Karlsruher Institut für Technologie (KIT), 2018. 298 pp. DOI: 10.5445/IR/1000085709.

[2] Bogdan Povh. *Teilchen und Kerne : Eine Einführung in die physikalischen Konzepte*. Ed. by Klaus Rith et al. 9. Aufl. 2014. Springer-Lehrbuch, SpringerLink : Bücher. Berlin, Heidelberg: Springer Spektrum, 2014. ISBN: 978-364-23782-2-5. URL: http://swbplus.bsz-bw.de/bsz39819646xcov.htmhttps://doi.org/10.1007/978-3-642-37822-5.

[3] Fabian Schenkel. *Search for s-channel Single Top Quark Production at a Center-of-Mass Energy of 13 TeV with the CMS Experiment*. MS. Karlsruhe Institute of Technology, Masterarbeit, 2017. 2017. URL: https://ekp-invenio.physik.uni-karlsruhe.de/record/48922.

[4] Max Welsch. *Trennung von Signal und Untergrund mit TensorFlow in einer Suche nach ttH-Produktion am CMS-Experiment*. BA. Karlsruher Institut für Technologie (KIT), Bachelorarbeit, 2017. 2017. URL: https://ekp-invenio.physik.uni-karlsruhe.de/record/48895.

[5] Wikipedia contributors. *Standard Model — Wikipedia, The Free Encyclopedia*. [Online; accessed 03-October-2018]. 2018. URL: https://en.wikipedia.org/w/index.php?title=Standard_Model&oldid=861946503.

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