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Boris Lemmer

Spin Correlations in $t\bar{t}$ Events from pp Collisions

Measured at $\sqrt{s} = 7$ TeV in the Lepton + Jets Final State with the ATLAS Detector

Doctoral Thesis accepted by
the University of Göttingen, Germany

Springer

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Supervisor's Foreword

One of the oldest questions of mankind is "what is the world is made of?" and, furthermore, what holds Nature's fundamental building blocks together to make the world as we see it?. While initially such questions were addressed via philosophical approaches, the last two centuries brought a wealth of new insights and information, in particular by using modern ideas of science and technology. Digging deeper and deeper into the structure of matter, quantum mechanics and quantum field theory were invented in order to successfully describe the behaviour of elementary particles and their interactions in the microcosm at the highest level of precision matching that of corresponding experiments. Although not directly accessible to visual inspection, elementary particles and their interactions have been subject to investigations via scattering experiments since the breakthrough of the famous Rutherford experiment almost exactly 100 years ago. Similar in spirit, just as much larger energies, modern particle physics experiments study the six known quarks and leptons along with their interactions. The heaviest of all known elementary particles today is the top-quark. With a mass of 175 GeV (1 GeV corresponds to the mass of an individual proton, i.e. the nucleus of a hydrogen atom), it is heavier than any known fermion (quarks and leptons) and than any known gauge boson including the recently discovered Higgs. Consequently, it behaves differently from any other quark. With a lifetime of about 5×10^{-25} sec, the top-quark decays before it can hadronize and form bound states. Hence, it is the only quark that can be studied without any disturbing chromomagnetic interactions. Since its discovery by the Fermilab experiments CDF and D0 at the Tevatron in 1995, these experiments collected a lot of information about this quark. Still, only in recent years, measurements of fundamental top-quark properties such as its mass or its electric charge were made with some precision, while its spin was only indirectly investigated via precise measurements of the top-antitop-quark pair-production cross-section at increasing center-of-mass energy. The most recent step therein was only possible due to the startup of the Large Hadron Collider (LHC) at CERN. After more than 20 years of preparation and with an initial center-of-mass energy of

7 and 8 TeV in 2010 to 2012 and records in beam luminosity, the LHC quickly turned literally into a real top-quark factory.

Boris Lemmer joined the large international ATLAS collaboration in 2010. He worked on the operation and calibration of the pixel detector, Monte Carlo validation studies and parameterised the resolution of the ATLAS detector for the energy and momentum measurement of jets, electrons and muons. Based on this vast experience, Boris Lemmer joined a small team in Göttingen to work on a kinematic likelihood fitter tool "KLFitter" for the kinematic reconstruction of top-antitop-quark events with subsequent decay to leptons and jets. His particular focus was the extraction of transfer-resolution functions for the energy or momentum measurements of jets and leptons with the ATLAS detector. Such transfer functions are a key ingredient in the kinematic fitter and hence of crucial importance. Subsequent performance studies showed that this KLFitter tool was superior to and outperformed any other reconstruction technique proposed. Consequently, it was then used in numerous top-quark physics data analysis by ATLAS and also studied by CMS. Boris Lemmer et al. published the algorithm and first performance studies in Nuclear Instruments and Methods A in 2014. Based on this achievement, Boris worked out a study of the top-quark spin. Resulting from it exceptionally short lifetime, the top-quark decays before it hadronizes, in contrast to all other quarks, and passes its quantum numbers to its decay products in an undisturbed way. The terminology "quark" implies that the top is a spin-1/2 particle, i.e. a fermion. The spin of a particle is a very fundamental property which determines it's behaviour in many respects. However, strictly speaking, this property had not been directly measured precisely by the Tevatron experiments. Boris' PhD and his thesis aim at performing a direct test of the top-quark spin by making an improved measurement of the top-antitop spin correlation. A first real measurement was by ATLAS in 2011 in the dilepton channel. The dominant production mechanism is top-quark pair production via Quantum Chromo Dynamics (QCD), which produces unpolarised top-quarks. Here, top-quarks can be produced via gluon initiated (spin 1 + 1) or via quark-initiated (spin 1/2 + 1/2) processes with correlated or anti-correlated top-antitop-spins, where the fraction of the two groups of processes depends on the proton–proton center-of-mass energy. The measurement of the top-antitop spin correlation allows a direct confirmation of the top to be a spin-1/2 particle. A measurement of the energy-dependence allows further tests of the underlying production mechanism. The top-antitop spin correlation can deviate significantly from the Standard Model expectation in BSM models. For example, top-quark production via intermediate Z' bosons would tend to result in correlated spins, while the decay of a scalar particle such as a Higgs boson into top-antitop would yield anticorrelated top spins. The spin correlation can be measured via the anti-symmetric electroweak top $\rightarrow$ Wb decay and the anti-symmetric subsequent W-boson decay ($W \rightarrow l\nu$, qq'). In the leptonic W-boson decay, the up-type and the down-type fermions are easily identified, yielding a simple and powerful spin-correlation analysis in the dilepton decay channel. In his PhD thesis, Boris Lemmer focused on the complementary and statistically independent lepton+jets channel, which is more difficult to analyse.

Boris' PhD thesis represents the first analysis of this kind in the lepton+jets channel. It is original and the methods used to reconstruct the top-antitop final state as well as to identify the up-type and the down-type quarks in the final state are challenging and highly innovative. His analysis uses a data set of 5 fb^{-1} recorded by the ATLAS experiment at a center-of-mass energy of 7 TeV. It is based on the kinematic event reconstruction and decay angles with respect to the down-type quark or the b-quark as spin analysers. He pays particular attention to the correlation of different angles. He also studies jet-charge techniques and charm tagging algorithms in order to improve the up-type and down-type quark identification for jets from hadronic *W*-boson decays. A strong focus is the final statistical data analysis as well as the careful and detailed study of correlations of various systematic uncertainties from which he manages to extract significant information on the spin-correlation and hence improve the precision of this measurement. The fact that his measurement of the top-antitop-quark spin-correlation in the lepton plus jets decay channel yields almost the same precision as the measurement in the much easier to analyse dilepton channel was unexpected and a big surprise to everyone. His analysis and result are published in Physics Review D, to a large extent thanks to Boris's tireless efforts.

Boris Lemmer's PhD analysis is highly relevant to fundamental properties of the top-quark and very innovative. His result is consistent with that of the dilepton channel and indicates that the top is indeed a spin-1/2 particle, i.e. the top-"quark". His impressive achievements and results as well as his outstanding contributions to the field of science communication via the Göttingen rent-a-scientist program, the physics show "Zauberhafte Physik", the successful participation in numerous science slams and his German championship in 2011, his book "Bis(s) ins Innere des Protons" and the support by the German National Scholarship Foundation convinced many colleagues, so that he was awarded the Berliner-Ungewitter PhD thesis prize 2014 by the faculty of physics at the Georg-August-Universität Göttingen. Congratulations for this award and your impressive and wonderful achievements!

June, 2015 Prof. Arnulf Quadt

Abstract

The top quark decays before it hadronises. Before its spin state can be changed in a process of strong interaction, it is directly transferred to the top quark decay products. The top quark spin can be deduced by studying angular distributions of the decay products. The Standard Model predicts the top/anti-top quark ($t\bar{t}$) pairs to have correlated spins. The degree is sensitive to the spin and the production mechanisms of the top quark. Measuring the spin correlation allows to test the predictions. New physics effects can be reflected in deviations from the prediction. In this thesis the spin correlation of $t\bar{t}$ pairs, produced at a center-of-mass energy of $\sqrt{s} = 7$ TeV and reconstructed with the ATLAS detector, is measured. The dataset corresponds to an integrated luminosity of 4.6 fb^{-1}. $t\bar{t}$ pairs are reconstructed in the $\ell +$ jets channel using a kinematic likelihood fit offering the identification of light up- and down-type quarks from the $t \rightarrow bW \rightarrow bq\bar{q}'$ decay. The spin correlation is measured via the distribution of the azimuthal angle $\Delta\phi$ between two top quark spin analyzers in the laboratory frame. It is expressed as the degree of $t\bar{t}$ spin correlation predicted by the Standard Model, f^{SM}. The results of

$$\begin{aligned} f^{\text{SM}}(\Delta\phi(\text{charged lepton, down-type quark})) &= 1.53 \pm 0.14\,(\text{stat.}) \pm 0.32\,(\text{syst.}),\\ f^{\text{SM}}(\Delta\phi(\text{charged lepton, } b\text{-quark})) &= 0.53 \pm 0.18\,(\text{stat.}) \pm 0.49\,(\text{syst.}),\\ f^{\text{SM}}(\Delta\phi(\text{combined})) &= 1.12 \pm 0.11\,(\text{stat.}) \pm 0.22\,(\text{syst.}), \end{aligned}$$

are consistent with the Standard Model prediction of $f^{\text{SM}} = 1.0$.

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