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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

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ISSN 2190-5053

Springer Theses

ISBN 978-3-319-18931-4

DOI 10.1007/978-3-319-18932-1

ISSN 2190-5061 (electronic)

ISBN 978-3-319-18932-1 (eBook)

Library of Congress Control Number: 2015940750

Springer Cham Heidelberg New York Dordrecht London

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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 its 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 its 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 ($W \rightarrow lv, qq'$). 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 $\ell + \text{jets}$ 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 $f^{\text{SM}} = 1.0$.

Contents

1	Introducing the Standard Model, Top Quarks and Spin Correlation	1
1.1	The Standard Model of Particle Physics	4
1.1.1	Strong Interaction	6
1.1.2	Electroweak Interaction	8
1.1.3	Electroweak Symmetry Breaking	10
1.1.4	Limitations of the Standard Model	12
1.2	Proton Structure	13
1.3	The Top Quark	15
1.3.1	Top Quark Production and Decay	16
1.3.2	Measured Top Quark Properties	23
1.4	Top Quark Polarization and Spin Correlation in $t\bar{t}$ Events	27
1.4.1	Choice of the Spin Quantization Axis	29
1.4.2	Spin Analysing Powers	32
1.4.3	Observables with Sensitivity to $t\bar{t}$ Spin Correlation	34
1.4.4	Measurement of f^{SM}	37
1.5	Sensitivity of $t\bar{t}$ Spin Correlation to Physics Beyond the Standard Model	39
1.5.1	New Physics in the $t\bar{t}$ Production	39
1.5.2	New Physics in the $t\bar{t}$ Decay	41
1.6	Recent Measurements of $t\bar{t}$ Spin Correlation	41
1.6.1	Recent Top Polarization Measurements	41
1.6.2	Recent Spin Correlation Measurements	42
	References	46
2	Experimental Setup	57
2.1	The LHC	57
2.2	The ATLAS Detector	59
2.2.1	Inner Detector	60
2.2.2	Calorimeters	61
2.2.3	Muon Chambers	63

2.2.4	Magnet System	64
2.2.5	Trigger System	65
2.2.6	Luminosity Measurement	65
	References.	66
3	Analysis Objects	69
3.1	Electrons	70
3.2	Muons	73
3.3	Jets	74
3.3.1	Jet Vertex Fraction.	76
3.3.2	B-Tagging	77
3.4	Missing Transverse Momentum	79
3.5	τ Leptons	80
	References.	80
4	Dataset, Signal and Background Modelling	83
4.1	Dataset	83
4.2	$t\bar{t}$ Signal Samples.	85
4.3	MC Driven Backgrounds	86
4.3.1	Single Top	86
4.3.2	Diboson	86
4.3.3	W +Jets	86
4.3.4	Z +Jets	86
4.4	Data Driven Backgrounds.	87
4.4.1	Fake Lepton Estimation	87
4.4.2	W +jets Normalization.	89
4.4.3	W +jets Flavour Composition.	90
	References.	91
5	Event Selection and Reconstruction	93
5.1	$t\bar{t}$ Selection in the Lepton+Jets Channel	93
5.1.1	e + jets Selection.	94
5.1.2	μ + jets Selection	94
5.1.3	Yields After Selection	95
5.2	Data/MC Agreement	96
5.3	Mismodelling of the Jet Multiplicity.	97
5.4	Reconstruction of $t\bar{t}$ Events with a Kinematic Likelihood Fit.	98
5.5	Transfer Functions	102
5.6	KLfitter Extension for Up/Down-Type Quark Separation	108
5.7	Reconstruction Efficiencies and Optimizations.	110
5.8	KLfitter Setup	118

- 5.9 Comparison to Other Reconstruction Methods 118
 - 5.9.1 P_T Max 118
 - 5.9.2 Topological Method 119
 - 5.9.3 Performance Comparison 119
- References. 120

- 6 Analysis Strategy 121**
 - 6.1 Choice of Observable 121
 - 6.2 Spin Analyser Validation 123
 - 6.3 Binned Likelihood Fit 125
 - 6.3.1 Analysis Channels 128
 - 6.3.2 Usage of Priors 128
 - 6.3.3 Systematic Uncertainties as Nuisance Parameters 129
 - 6.3.4 Jet Multiplicity Correction 130
 - 6.3.5 Fit Parameters 130
 - 6.4 Method Validation 130
 - 6.5 Expected Statistical Uncertainty 132
 - 6.6 Analyser Correlation 132
- References. 134

- 7 Systematic Uncertainties 135**
 - 7.1 List of Systematic Uncertainties. 136
 - 7.1.1 Jet Uncertainties 136
 - 7.1.2 Lepton Uncertainties 138
 - 7.1.3 Missing Transverse Momentum 139
 - 7.1.4 Luminosity 140
 - 7.1.5 Uncertainties on the Background 140
 - 7.1.6 $t\bar{t}$ Modelling Uncertainties. 141
 - 7.2 Test for NP Inclusion 151
 - 7.3 Evaluation of Non-Profileable Uncertainties 153
 - 7.4 Important Aspects of Systematic Uncertainties. 154
- References. 156

- 8 Results and Discussion 159**
 - 8.1 Single Channel Results. 159
 - 8.2 Combined Fits Without Nuisance Parameters 160
 - 8.3 Combined Fits Using Nuisance Parameters 161
 - 8.4 Final Fit Results 161
 - 8.5 Fit Consistency Checks 162
 - 8.5.1 Post-fit Plots 162
 - 8.5.2 Posterior PDFs 163
 - 8.5.3 Nuisance Parameter Postfit Values 165

8.6	Discussion of Uncertainties	170
8.6.1	Dominating Uncertainties	170
8.6.2	Expected Deviations.	173
8.7	Spin Analyzer Consistency Checks	176
	References.	178
9	Summary, Conclusion and Outlook	179
9.1	Summary of Results.	179
9.2	Conclusion	181
9.3	Outlook	183
9.3.1	Reduction of Systematic Uncertainties	183
9.3.2	Dileptonic $t\bar{t}$ Event Suppression.	183
9.3.3	Usage of Jet Charge for $t\bar{t}$ Reconstruction.	184
9.3.4	Future Measurements of $t\bar{t}$ Spin Correlation	185
	References.	186
	Appendix A: Spin Correlation Matrices	187
	Appendix B: Used Datasets	189
	Appendix C: Pretag Yields.	199
	Appendix D: Control Plots of the Signal Regions Used for Fitting	201
	Appendix E: KL Fitter Likelihood Components	207
	Appendix F: Down-Type Quark p_T Spectrum in POWHEG+PYTHIA	209
	Appendix G: Posterior Distributions of Fit Parameters	211
	Appendix H: Postfit Values of Nuisance Parameters	215
	Appendix I: Most Significant Uncertainties.	217
	Appendix J: $\Delta\phi$ for Different MC Generators.	219
	Appendix K: Alternative $t\bar{t}$ Modeling	221
	Appendix L: Jet Charge	223
	Curriculum Vitae	227
	Index	231

List of Figures

Figure 1.1	a Indirect determinations of the <i>top</i> quark mass via fits to electroweak observables, results of direct measurements as well as lower bounds from direct searches and <i>W</i> boson width analyses [22]. b Measured masses of the <i>W</i> boson (M_W) and the <i>top</i> quark (m_t), shown in <i>green bands</i> . These are compared to electroweak fit results excluding the direct measurements of m_t and M_W (<i>blue area</i>) and excluding m_t , M_W and the measured Higgs boson mass M_H (<i>grey area</i>) [23].	3
Figure 1.2	Fermions (quarks and leptons) and gauge bosons of the Standard Model and some of their basic properties. The small boxes indicate the fields to which the particles couple: <i>colour</i> (<i>c</i>), <i>electromagnetic</i> (<i>e</i>) and <i>weak</i> (<i>w</i>). The number in the <i>upper right corner</i> represents the electric charge.	5
Figure 1.3	The measured dependence of α_s on the energy scale $\sqrt{Q^2}$ [54].	8
Figure 1.4	Parton distribution function of the nominal CT10 set at $Q^2 = m_t^2$. The minimal average proton momentum fractions x for $t\bar{t}$ production are shown for Tevatron ($\sqrt{s} = 2$ TeV) and the LHC ($\sqrt{s} = 7$ TeV)	14
Figure 1.5	$t\bar{t}$ production via strong interactions. a Quark/antiquark annihilation, b–d gluon fusion.	17
Figure 1.6	Comparison of the measured $t\bar{t}$ cross sections at the Tevatron and the LHC using input values from [97–106] and the predictions from [95]. The figure is taken from [107]	19
Figure 1.7	Single top quark production via electroweak interactions in a the <i>s</i> -channel, b the <i>t</i> -channel and c produced in association with a <i>W</i> boson (<i>Wt</i> channel).	19

Figure 1.8	The decay of a $t\bar{t}$ pair in the $\ell + \text{jets}$ channel.	22
Figure 1.9	a Decay channels of $t\bar{t}$ pairs and their relative rates. b A more detailed view of (a) including migration effects caused by τ leptons	22
Figure 1.10	World combination of the top quark mass [47] together with the input results [128–138] and the dedicated Tevatron [126] and LHC combinations [127]	23
Figure 1.11	Comparison of the measurements of A_{FB} and A_{C} [145, 152–154] to BSM scenarios from [150, 151] as shown in [153]	25
Figure 1.12	$t\bar{t}$ spin configuration at the production threshold limit for a $q\bar{q}$ annihilation and b gg fusion.	29
Figure 1.13	Illustration of a the helicity basis and b the off-diagonal basis. c The angle θ between a spin analyser (<i>here</i> the charged lepton) and the spin basis in the top quark rest frame. The <i>blue arrows</i> indicate the spin quantization axes.	30
Figure 1.14	a $t\bar{t}$ production cross section as a function of the invariant mass $M_{t\bar{t}}$ of the $t\bar{t}$ system for production at the LHC (pp collisions at $\sqrt{s} = 14$ TeV) and the Tevatron ($p\bar{p}$ collisions at $\sqrt{s} = 2$ TeV) [176]. b Decomposition of the LHC cross section ($\sqrt{s} = 14$ TeV) into gg fusion and $q\bar{q}$ annihilation [172].	31
Figure 1.15	Distributions of $\cos\theta_i, \cos\theta_j$ at parton level using a the helicity and the b maximal basis [180]. The charged leptons from the dilepton channel served as spin analysers. MC@NLO was used generating events with SM spin correlation ($A = \text{SM}$) and uncorrelated $t\bar{t}$ events ($A = 0$). The notation A used in the figure corresponds to the spin correlation C used in this thesis	35
Figure 1.16	Distributions sensitive to $t\bar{t}$ spin correlation [180]: a S-Ratio. b Azimuthal angle between the two analysers in the laboratory frame. The charged leptons from the dilepton channel served as spin analysers. MC@NLO was used to generate events with SM spin correlation ($A = \text{SM}$) and uncorrelated $t\bar{t}$ events ($A = 0$). The notation A used in the figure corresponds to the spin correlation C used in this thesis.	36
Figure 1.17	Azimuthal angle between the two charged leptons from $t\bar{t}$ decays produced in $p\bar{p}$ collisions at $\sqrt{s} = 2$ TeV [186]. The SM prediction (<i>solid line</i>) is compared to the scenario of uncorrelated $t\bar{t}$ pairs (<i>dashed line</i>). A top mass of 120 GeV was assumed	36

Figure 1.18 **a** An example for modified $t\bar{t}$ production. A heavy scalar ϕ is replacing the virtual gluon. **b** An example for a modified $t\bar{t}$ decay. The W boson is replaced by a scalar charged Higgs boson. 39

Figure 1.19 **a** Modifications of A_{FB} and C_{helicity} by several BSM scenarios [197]. **b** $\Delta\phi(l^+, l^-)$ distributions for top squarks in the dilepton channel, simulated at $\sqrt{s} = 8$ TeV [198]. **c** Spin analysing powers in top decays via a charged Higgs H^+ [199]. **d** Modifications of $\Delta\phi(b, \bar{b})$ by the decay $t \rightarrow H^+ b$ [199]. 40

Figure 1.20 **a** Distributions of the angles between the charged leptons and the helicity spin basis. The data was fit with a CP conserving polarization hypothesis [201]. **b** Unfolded distribution of the angle between the charged lepton and the helicity spin basis [188]. 42

Figure 1.21 Results of measured $t\bar{t}$ spin correlations at the Tevatron in the $\ell + \text{jets}$ channel. **a** Likelihood discriminant R for the analysis in the $t\bar{t} \ell + \text{jets}$ channel of the D0 analysis. **b** Result of the fitted $\cos\theta_l \cdot \cos\theta_d$ (beam line basis) distribution of the CDF analysis [206]. 43

Figure 1.22 LHC measurements of the $\Delta\phi(l^+, l^-)$ distributions in $t\bar{t}$ events decaying in the dilepton channel. **a** ATLAS result leading to observation of spin correlation [187]. **b** Unfolded distribution with subtracted background as measured by CMS together with NLO predictions [188]. 44

Figure 1.23 ATLAS measurements using 4.6 fb^{-1} of data selecting $t\bar{t}$ events in the dilepton channel and fitting **a** the S -Ratio and **b** the $\cos\theta_{l^+} \cos\theta_{l^-}$ for the maximal basis [180]. 44

Figure 1.24 Overview of ATLAS results of measurements of the $t\bar{t}$ spin correlation for the 4.6 fb^{-1} 7 TeV dataset [180]. 45

Figure 2.1 The CERN accelerator complex ©CERN 58

Figure 2.2 The ATLAS detector with its components [8]. 60

Figure 2.3 The ATLAS inner detector [8]. 62

Figure 2.4 The ATLAS calorimeter system [8]. 63

Figure 2.5 The ATLAS muon system [8]. 64

Figure 3.1 Illustration of a particle detection process and the different levels of object descriptions 70

Figure 3.2 An ATLAS event display showing a $t\bar{t}$ candidate event with both top quarks decaying leptonically, one into an electron, the other one into a muon. The event is shown in the r/ϕ plane (*upper left*) and the r/z plane (*lower left*). The electron is represented by the *green track* pointing to the corresponding clusters in the ECal. The signature of the muon is visible as *red track* passing the

	muon spectrometer. The two jets in the event were both tagged as b -jets. Their secondary vertices are visible in the <i>zoomed view</i> of the primary vertex (<i>upper right</i>). Picture translated from [2], original version from [3]	71
Figure 3.3	Identification efficiency for different electron types as a function of pile-up [6]	72
Figure 3.4	a Difference between the origin corrected η_{jet} and the true η_{jet} in bins of the calorimeter jet energy calibrated with the EM+JES scheme as a function of η_{detector} [14]. b Jet response $R_{\text{EM}}^{\text{jet}} = E_{\text{EM}}^{\text{jet}}/E_{\text{truth}}^{\text{jet}}$ [14].	75
Figure 3.5	Illustration of the principle of the Jet Vertex Fraction variable. While for the <i>left jet</i> all tracks originate from PV_1 and none from PV_2 , the <i>right jet</i> has only a certain fraction f of tracks from PV_2 and another fraction $1 - f$ from PV_1	76
Figure 3.6	a Distribution of the JVF variable for jets from the hard scattering process and for pile-up jets [17]. b Pile-up suppression by the application of the JVF cut, shown as stability of the number of reconstructed jets against the number of primary vertices for $Z + \text{jets}$ events [17]	77
Figure 3.7	Distribution of the b -jet multiplicity using a the default calibration based on di-jet events ($\text{pTrel} + \text{System8}$) [19] and b the combined calibration ($\text{pTrel} + \text{System8} + \text{dileptonic } t\bar{t}$) [20] for $t\bar{t}$ pairs decaying into an electron and at least four jets	78
Figure 3.8	Overview of b -tag scale factors using different calibration methods [20]	79
Figure 4.1	Evolution of the instantaneous luminosity delivered to ATLAS during data taking in 2010–2012 [2]	84
Figure 4.2	a Evolution of the integrated luminosity $\int \mathcal{L} dt$ delivered, recorded and accepted by the GRL for the 2011 dataset [2]. b The mean number of interactions per bunch crossing for the 2011 dataset [2].	84
Figure 4.3	Improvement by the choice of a new parameterization for the fake lepton estimate. Mismodelling is visible particularly in the $\Delta R(\text{lepton}, \text{jet})$ distributions: a old parameterization in p_T and η of the lepton. The template statistics uncertainty is shown for the prediction. b New parameterization with an additional $\Delta R(\text{lepton}, \text{jet})$ dependence. The template statistics uncertainty, the normalization uncertainty for the data driven yields and the theory uncertainty on the cross sections are shown for the prediction and propagated to the error band in the ratio	89

Figure 5.1	Yield for data (<i>points</i>) and the different Monte Carlo contributions (<i>filled histograms</i>) split into the different run periods for a the $e + \text{jets}$ channel and b the $\mu + \text{jets}$ channel. The default selection of at least four jets with at least one b -tagged jet was used.	96
Figure 5.2	Control distributions for the lepton p_T , η and ϕ distribution of the $e + \text{jets}$ (<i>top</i>) and $\mu + \text{jets}$ (<i>bottom</i>) channel ($n_{\text{jets}} \geq 4, n_{b\text{-tags}} \geq 1$).	97
Figure 5.3	Control distributions for the jet p_T , η and ϕ distribution of the $e + \text{jets}$ (<i>top</i>) and $\mu + \text{jets}$ (<i>bottom</i>) channel (all selected jets, $n_{\text{jets}} \geq 4, n_{b\text{-tags}} \geq 1$).	98
Figure 5.4	Control distributions for the jet p_T of the three highest p_T jets of the $e + \text{jets}$ (<i>top</i>) and $\mu + \text{jets}$ (<i>bottom</i>) channel ($n_{\text{jets}} \geq 4, n_{b\text{-tags}} \geq 1$).	99
Figure 5.5	Control distributions for the p_T of jet with the 4th highest p_T , the missing transverse momentum and W_{m^T} of the $e + \text{jets}$ (<i>top</i>) and $\mu + \text{jets}$ (<i>bottom</i>) channel ($n_{\text{jets}} \geq 4, n_{b\text{-tags}} \geq 1$).	100
Figure 5.6	Jet multiplicity using MC@NLO as $t\bar{t}$ signal generator. a $e + \text{jets}$ channel. b $\mu + \text{jets}$ channel	100
Figure 5.7	Jet multiplicity using POWHEG+PYTHIA as $t\bar{t}$ signal generator. a $e + \text{jets}$ channel. b $\mu + \text{jets}$ channel	101
Figure 5.8	Transfer function fits for a light jets, b b -jets, c electrons and d muons for truth energies/transverse momenta of about 100 GeV. The entries derived from a signal MC sample are fitted locally with a double Gaussian function, composed of a small and a big Gaussian function. The global TF fit is also shown	104
Figure 5.9	Estimation of parameters p_i as a function of E_{truth} for light jets in the region $0.0 \leq \eta < 0.8$. The parameters were estimated as functions of E_{truth} according to Table 5.4	105
Figure 5.10	Transfer functions for light jets with $0.0 \leq \eta < 0.8$. <i>Vertical lines</i> indicate the parton energies	106
Figure 5.11	Transfer functions for Neutrinos/ E_T^{miss} , parameterized as a function of ΣE_T	107
Figure 5.12	Description of the detector resolution effects for light jets at low energies. a $35 \leq E_{\text{jet}} < 45$ GeV, b $25 \leq E_{\text{jet}} < 35$ GeV	107
Figure 5.13	a p_T spectra for the three jet types from the hadronic top quark decay. b Weight of the MV1 b -tagger for different light quark types of the W decay. c Weight of the MV1 b -tagger for the three jet types from the hadronic top quark decay	109

Figure 5.14	Distribution of the b -tagging weights of the MV1 tagger versus the p_T of a jet for three types of jets: a b -jets coming directly from the top quark decay, b down-type quarks coming from the W boson and c up-type quarks coming from the W boson	109
Figure 5.15	Event properties and reconstruction efficiencies using KLFitter in the $\mu +$ jets channel. Numbers are given with respect to all events passing the event selection.	111
Figure 5.16	Reconstruction efficiencies using KLFitter in the $\mu +$ jets channel. Numbers are given with respect to all events passing the event selection (<i>solid line</i>) and to such events where all four jets passed to KLFitter were bi-uniquely matched to partons (<i>dashed line</i>).	112
Figure 5.17	Reconstruction efficiencies of b -quarks and down-type quarks as a function of a the number of reconstructed primary vertices, b the number of reconstructed jets, c the number of b -tagged jets, d the transverse momentum of the jets assigned to the down-type quark and the b -quark, e the logarithm of the KLFitter likelihood and f the KLFitter event probability	114
Figure 5.18	a Jet allocated to model partons by KLFitter (<i>coloured lines</i>) and the partons to which they were matched (x -axis). b η and p_T of down-type quarks for the full phase space, before event selection. The <i>red lines</i> indicate the cuts applied on reconstruction/detector level	116
Figure 5.19	Cuts on event properties and their effects on the statistics and reconstruction efficiencies for the a b -quark and b down-type quark	117
Figure 6.1	Distribution of the azimuthal angle between the charged lepton and the a down-type quark and the b b -quark in the laboratory frame [3]. The distributions show the full phase space on parton level without usage of cuts on p_T and η of the objects.	122
Figure 6.2	Distribution of the azimuthal angle between the charged lepton and the jet assigned to the a down-type quark and the b b -quark in the laboratory frame. The distributions use reconstructed quantities in the $\mu +$ jets channel after the event selection is applied. The shown uncertainties (barely visible) represent the MC statistics uncertainty	123
Figure 6.3	The weight of the MV1 b -tagger (<i>left</i>), the number of tagged jets (<i>centre</i>) and the p_T of the down-type quark candidate (<i>right</i>) for the $e +$ jets channel (<i>upper row</i>) and the $\mu +$ jets channel (<i>lower row</i>)	124

Figure 6.4 The p_T ranking index of the down-type quark jet (*left*), the index of b -quark jet from the hadronic top (*middle*) and the $\Delta\phi$ angle between the reconstructed hadronic b -quark and the down-type-quark (*left*) for the $e + \text{jets}$ channel (*upper row*) and the $\mu + \text{jets}$ channel (*lower row*). 125

Figure 6.5 The logarithm of the KLfitter likelihood (*left*) and the event probability (*right*) for the $e + \text{jets}$ channel (*upper row*) and the $\mu + \text{jets}$ channel (*lower row*) 126

Figure 6.6 **a** Linearity test for the combination of down-type quark and b -quark analysers. **b** Pull mean distribution for the combination of down-type quark and b -quark analysers 131

Figure 7.1 JES systematic uncertainty as a function of jet p_T . **a** Total in-situ contribution and components [1]. **b** Total JES uncertainty (without b -jet JES uncertainty) with $t\bar{t}$ ($\ell + \text{jets}$ channel) specific components [1] 137

Figure 7.2 Fitted f^{SM} values for the MSTW2008nlo68cl, CT10 and NNPDF2.3 PDF set and their corresponding error sets. The results are shown for the **a** Down-type quark, the **b** b -quark and **c** the full combination of the fit. 142

Figure 7.3 Fit values for f^{SM} for different values of the top quark mass. For each analyser, a linear fit is performed. 143

Figure 7.4 **a** Measured differential top quark cross section as a function of the top quark transverse momentum [21]. The unfolded data is compared to different generators. **b** Ratios of the NLO QCD predictions to the measured normalized differential cross sections for different PDF sets [21] 144

Figure 7.5 The p_T spectrum of **a** the leptonic and **b** the hadronic top quark. The unfolded data measurement of [21] is compared to MC@NLO and POWHEG + HERWIG. Here, results from the $\mu + \text{jets}$ channel are shown 144

Figure 7.6 $\Delta\phi$ distributions using the b -quark as analyser. **a** The $\Delta\phi$ distribution for the Standard Model expectation normalized to one. The contributions from the low and high top p_T region are indicated. **b** Same distributions as (**a**), but with the low and high top p_T region also normalized to one. As an example, the effect of reweighting is shown in (**d**): The SM and the uncorrelated $t\bar{t}$ sample are compared to the SM prediction, which is reweighted in top p_T [22]. The ratio plot shows the ratios uncorrelated over SM (*dashed*) and reweighted over SM (*red dash-dotted*) 146

Figure 7.7 $\Delta\phi$ distributions using the b -quark as analyser. **a** The $\Delta\phi$ distribution for the Standard Model expectation normalized to one. The contributions from the low and high top p_T region are indicated. **b** Same distributions as **(a)**, but with the low and high top p_T region also normalized to one. As an example, the effect of reweighting is shown in **(c)**: The SM and the uncorrelated $t\bar{t}$ sample are compared to the SM prediction, which is reweighted in top p_T [22]. The ratio plot shows the ratios uncorrelated over SM (*dashed*) and reweighted over SM (*red dash-dotted*) 147

Figure 7.8 The top p_T spectrum on parton level for different generators. The used top status codes were 155 for HERWIG and 3 for PYTHIA. The ratios are with respect to MC@NLO 148

Figure 7.9 **a** Width and **b** mean of the output f^{SM} distributions after fluctuation of the $t\bar{t}$ signal templates bins according to their MC statistics uncertainty. Poissonian fluctuations were applied to either only the SM $t\bar{t}$ spin correlation sample, the uncorrelated $t\bar{t}$ spin sample or both 150

Figure 7.10 An example nuisance parameter, tested on one template type and for several channels. Three channels are shown as example. **a** The systematic variations (*red* and *blue*) show clear significance with respect to the MC statistics (*green*) for all bins. **b** No bin itself is statistically significant, but the sum of differences is. **c** The uncertainty is clearly not significant 154

Figure 7.11 Effects of increased top quark p_T on the azimuthal angle between the lepton and the **a** Down-type quark and **b** b -quark. The MC@NLO sample with uncorrelated $t\bar{t}$ pairs is used to decouple spin and kinematic effects on the $\Delta\phi$ shape. Parton level quantities are used 155

Figure 7.12 Effects of increased p_T of the $t\bar{t}$ system on the azimuthal angle between the lepton and the **a** Down-type quark and **b** b -quark. The MC@NLO sample with uncorrelated $t\bar{t}$ pairs was used to decouple spin and kinematic effects on the $\Delta\phi$ shape. Parton level quantities were used 156

Figure 8.1 Comparison of single channel fit results using **a** the down-type quark and the **b** b -quark as spin analyser. The fits were performed without nuisance parameters. The quoted uncertainties are statistical. Next to the individual fit results the SM expectation (*green line*) and the result of the combined fit (*yellow band*) are shown. 160

Figure 8.2 Prediction of the SM spin correlation and uncorrelated $t\bar{t}$ pairs (*black dashed and dotted*) compared to data (*black dots*) and the best-fit result (*red line*) including uncertainties (*yellow area*). The ratios of SM and uncorrelated prediction (*black line*) as well as best-fit to data (*red line*) are shown. These plots show the four $e + \text{jets}$ channels using the down-type quark as analyser. 163

Figure 8.3 Prediction of the SM spin correlation and uncorrelated $t\bar{t}$ pairs (*black dashed and dotted*) compared to data (*black dots*) and the best-fit result (*red line*) including uncertainties (*yellow area*). The ratios of SM and uncorrelated prediction (*black line*) as well as best-fit to data (*red line*) are shown. These plots show the four $\mu + \text{jets}$ channels using the down-type quark as analyser 164

Figure 8.4 Prediction of the SM spin correlation and uncorrelated $t\bar{t}$ pairs (*black dashed and dotted*) compared to data (*black dots*) and the best-fit result (*red line*) including uncertainties (*yellow area*). The ratios of SM and uncorrelated prediction (*black line*) as well as best-fit to data (*red line*) are shown. These plots show the four $e + \text{jets}$ channels using the b -quark as analyser 165

Figure 8.5 Prediction of the SM spin correlation and uncorrelated $t\bar{t}$ pairs (*black dashed and dotted*) compared to data (*black dots*) and the best-fit result (*red line*) including uncertainties (*yellow area*). The ratios of SM and uncorrelated prediction (*black line*) as well as best-fit to data (*red line*) are shown. These plots show the four $\mu + \text{jets}$ channels using the b -quark as analyser. 166

Figure 8.6 Prior and posterior distributions for the fit parameters describing the background yields and the jet multiplicity correction for the full combination of the down-type quark and the b -quark analysers. 167

Figure 8.7 Postfit values of the nuisance parameters (*black lines*) for the full combination. The *grey vertical bands* behind the *lines* show the expected uncertainties on the nuisance parameters 168

Figure 8.8 Correlations between the fit parameters listed in Table 8.5 for the full combination of both analysers. 168

Figure 8.9 **a** PDF distribution as a function of the momentum fraction x for gluons. For both the CT10 and the HERPDF set the variations within the error sets are indicated by the *two lines*. **b** Relative deviations to the central value of the CT10, caused by the variations of the CT10 and the HERAPDF error sets 171

Figure 8.10	a $\Delta\phi(l, d)$ distribution in the $\mu + \text{jets}$ channel for the samples with increased and decreased initial and final state radiation. b $\Delta\phi(l, b)$ distribution in the $\mu + \text{jets}$ channel for the samples with increased and decreased initial and final state radiation	171
Figure 8.11	Number of b -tagged jets for POWHEG+PYTHIA and POWHEG+HERWIG in the $\mu + \text{jets}$ channel. Events containing τ leptons were vetoed and both samples were reweighted to the same top quark p_T spectrum.	172
Figure 8.12	Fit results for f^{SM} using pseudo data reweighted to different PDF sets and error sets. a Combined fit using the down-type quark. b Combined fit using the b -quark	174
Figure 8.13	Comparison of the $\Delta\phi$ distribution between MC@NLO (<i>black</i>) and POWHEG (<i>red</i>) using a the down-type quark and b the b -quark as analyser. The <i>dashed distribution</i> shows the POWHEG spectrum reweighted to match the top p_T distribution of MC@NLO	175
Figure 8.14	a Compatibility check for the results of the down-type quark and the b -quark combination. Only statistical uncertainties, the nuisance parameter uncertainties, the renormalization/factorization scale and the top p_T were used as uncertainties (<i>left</i>). b As a cross check the test was repeated without the top p_T uncertainty, but with ISR/FSR and PS/hadronisation uncertainty added.	177
Figure 9.1	Distributions of the stacked. a $\Delta\phi(l, d)$ and b $\Delta\phi(l, b)$ distributions for the combined fit [1]. The result of the fit to data (<i>blue</i>) is compared to the templates for background plus $t\bar{t}$ signal with SM spin correlation (<i>red dashed</i>) and without spin correlation (<i>black dotted</i>). The ratios of the data (<i>black points</i>), of the best fit (<i>blue solid</i>) and of the uncorrelated $t\bar{t}$ prediction to the SM prediction are also shown	180
Figure 9.2	Comparison of $t\bar{t}$ spin correlation measurements. The results of [1–7] using different observables have been divided by their SM expectations to compare a common f^{SM}	181
Figure 9.3	Normalized distributions of a the E_T^{miss} , b transverse W boson mass and the c logarithm of the likelihood from KLFitter. The distributions are shown for reconstructed simulated quantities of $t\bar{t}$ pairs decaying into the $\ell + \text{jets}$ channel and the dilepton channel	184
Figure 9.4	Charge of a jet matched to an up and anti-up quark using the a charge of the jet track with the highest p_T and b the weighted charge using all tracks	185