Measurement of top quark polarization in dileptonic top-antitop quark events using the ATLAS detector

Ralph Schäfer for the ATLAS Collaboration

DESY, Notkestraße 85, 22607 Hamburg, Germany

DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-02/55

1 Introduction

The top quark polarization is an interesting quantity to probe the Standard Model (SM) of particle physics. Due to its large mass of 173.2 ± 0.9 GeV [1], the top quark's lifetime is an order of magnitude smaller than the hadronization time scale [2], that means it decays before hadronization takes place and offers the opportunity to study a bare quark. This allows us to measure the top quark polarization since the top quark's spin information is transported to the decay products of the W boson. In the SM, top quark pairs are mainly produced unpolarized due to parity conservation in QCD. A small contribution from electroweak effects gives rise to a polarization of 0.003 [3]. New physics models involving anomalous couplings could lead to a significant polarization, in particular models also describing the forward-backward asymmetry (A_{fb}) measured at the Tevatron [4, 5] often include a non-zero polarization that could be observable at the LHC. A first study of the polarization has already been performed at the Tevatron [4] and is compatible with the SM expectation.

Polarization affects the angular distribution of the final state particle. For the polar angle θ of any final state particle (labelled by the index i) with respect to a certain quantization axis, the distribution is described by

$$W(cos\theta_i) = \frac{1}{2}(1 + \alpha_i P cos\theta_i), \tag{1}$$

where P is the polarization and α_i is the spin analyzing power of the corresponding particle i (charged leptons in this analysis) [6]. It describes the correlation between the spin direction of the top quark and the momentum direction of the final state particle and varies depending on the particle type between 0 and 1 with the latter being the maximum. For charged leptons, the spin analyzing power is 1 at leading order [6]. To analyze both top quarks in the event, the measurement is performed in the dilepton final state where both W bosons decay leptonically. This final state gives us three independent channels to

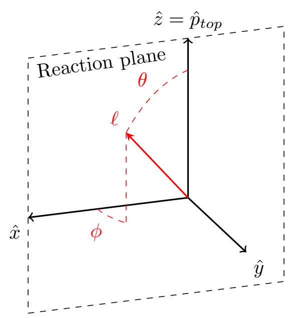


Figure 1: Sketch of the construction of the angle θ between the top and lepton l.

define that depend on the lepton type, namely ee, $e\mu$ and $\mu\mu$.
In the absence of polarization, the distribution according to Eqn. 1 will be flat, whereas polarization introduces an additional term linear in terms of $cos\ \theta$. As a quantization axis, the helicity axis of the parent top quark is taken. The angle θ is then defined by the polar angle of the momentum direction of the lepton in the top rest frame and the momentum direction of the top in the top-antitop rest frame (see Fig. 1).

2 Selection and background modelling

The measurement [7] is performed using 4.7 fb^{-1} of proton-proton collision data taken at a center of mass energy of 7 TeV at the LHC with the ATLAS detector [8]. Our estimates for the top-antitop signal and background containing two prompt leptons (Z+jets, single top and diboson production) are taken from Monte Carlo. As generator for the signal, MC@NLO [9] is used. Backgrounds containing non-prompt leptons or non-leptonic particles passing the lepton selection (called fakes) are measured via a data-driven approach, the so-called matrix method. [10]
In order to enhance the signal events and suppress background contributions, kinematic cuts are applied to events fulfilling the trigger condition. We require exactly two oppositely charged electrons or muons with one of them matching the object that fired the trigger. At least two jets have to be reconstructed in each event. The dilepton invariant mass m_{ll} in the ee and $\mu\mu$ has to be higher than 15 GeV and additionally it has to be more than 10 GeV away from the Z boson mass. This cut on m_{ll} suppresses the large background coming from Z boson production and $q\bar{q}$ resonances. These two channels also have a cut on the E_T^{miss} [1], which has to be higher than 60 GeV and accounts for the two neutrinos from the W bosons from the top pair. For the $e\mu$ channel, the sum of leptons' and jets' E_T has to be larger than 130 GeV. After applying the selection, around 8000 dilepton events remain to study the top quark polarization. Table 1 shows the event yields of signal, background and data for the different channels. One should note that in the ee and $\mu\mu$ channels, the shape for the $Z \to ee$ and $Z \to \mu\mu$ background in the corresponding channel are taken from Monte Carlo, but a scale factor is derived from data and applied to the background [7].

Source	ee	$e\mu$	$\mu\mu$
$t\bar{t}$	570	4400	1660
Bkgd.	110	700	320
Total	690	5000	1980
Uncert.	± 80	± 500	± 180
Data	740	5328	2057

Table 1: Event yields of signal, background (both rounded) and data after applying the selection along with their total uncertainty. [7]

3 Event reconstruction

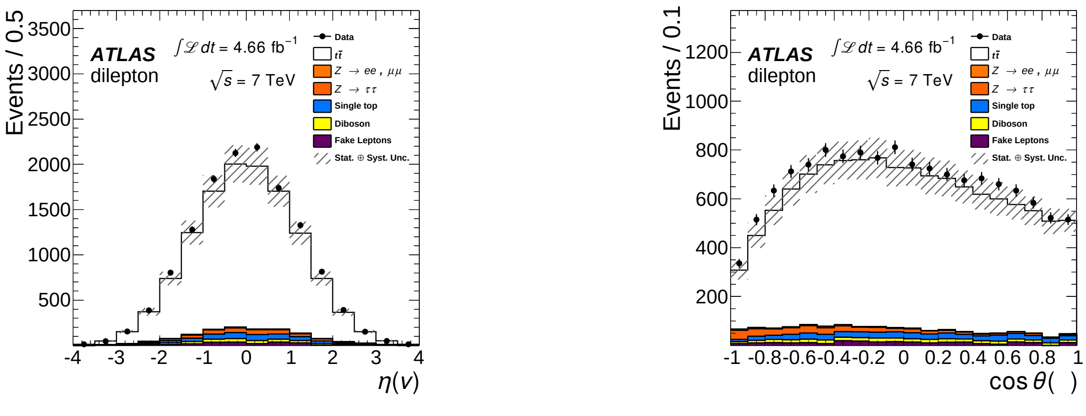
In order to measure the angle θ it is mandatory to reconstruct the $t\bar{t}$ system, which requires the information of all the final state particles. However, the two neutrinos from the W boson decays are only weakly interacting and leave undetected. This leads to an underconstrained system for the reconstruction with 18 kinematic variables from the momentum vectors of the

[1] E_T^{miss} is the magnitude of the negative vectorial sum of the transverse components of all calorimeter cells, corrected for the reconstructed muon momenta.

final state particles, of which only 12 are known. By fixing the top quark and W boson masses to the PDG [11] values we get four additional constraints. With the measured E_T^{miss} information, one could then solve the kinematic equations, but would end up with some ambiguity in the assignment of the leptons and jets to the corresponding top quark when reconstructing it. This ambiguity even increases for every additional reconstructed jet. To circumvent a random choice in the lepton-jet assignment, this analysis uses the so called Neutrino Weighting Tool [12] to reconstruct the top quarks and therefore the whole $t\bar{t}$ system. Instead of using the E_T^{miss} directly for the kinematic equations, it makes a hypothesis on the pseudorapidity η for each neutrino, calculates their longitudinal momenta (up to two solutions due to a quadratic equation) and constructs a weight w by comparing the measured E_T^{miss} with the calculated transverse momentum components $p_{x,y}$ of the two neutrinos ν_1 and ν_2:

$$w = \prod_{i=x,y} exp\left(-\frac{(E_i^{miss} - p_{i,\nu 1} - p_{i,\nu 2})^2}{2\sigma^2_{E_T^{miss}}}\right). \tag{2}$$

The E_T^{miss} resolution $\sigma_{E_T^{miss}}$ is a function of E_T^{miss} and the same within uncertainties for Monte Carlo and data [13]. The more compatible the E_T^{miss} information is with the neutrino p_T derived from the given neutrino η, the higher the weight w.
The η-hypothesis is based on the generated η distribution of the neutrinos, which is described in $t\bar{t}$ MC by a Gaussian distribution of mean 0 and unit width. For each event, 100 assumptions on both η_{ν_1} and η_{ν_2} are made according to this distribution and the weight w is computed for each lepton-jet combination. Additionally, all the jet energies are smeared 50 times to take into account a nominal jet resolution of approximately 3 % and the weights get recomputed each time. The solution with the highest weight is eventually taken as best guess for the reconstruction of the $t\bar{t}$ system. Figure 2(a) shows the data-expectation comparison of the neutrino pseudorapidity after reconstruction and is well described over the whole range. Looking



(a) Neutrino pseudorapidity

(b) $cos\ \theta$ for positive and negative leptons

Figure 2: Comparison of predicted signal+background and data events after reconstructing the event with the Neutrino Weighting for all channels combined. [7]

at the $cos\ \theta$ distribution (see Fig. 2(b)) for positive and negative leptons and all channels combined, we can see the same good agreement for the shape of the distribution. The shape is distorted due to detector acceptance and kinematic cuts on the events.

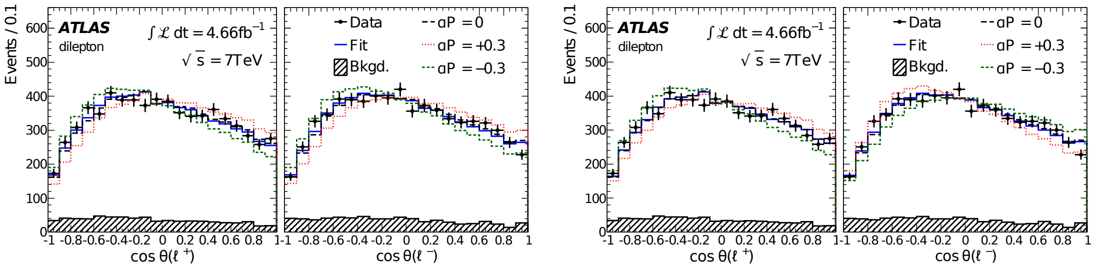
Since the kinematic equations for the longitudinal component of the neutrino momentum can give non-real solutions, it is not always possible to reconstruct the system. The efficiency of obtaining at least one physical solution for each event is 85% in $t\bar{t}$ MC.

4 Templates and fitting

After selecting and reconstructing our events to get the *cos* θ value of each lepton-top pair, a value for αP is extracted from the *cos* θ distribution, which is done by performing a binned likelihood template fit. The necessary templates with non-zero top quark polarization are obtained by reweighting each event with a weight w_{rew} based on the double-differential cross section for $t\bar{t}$ production [14]

$$w_{rew} = \frac{1 + B_1 \cos\theta_1 + B_2 \cos\theta_2 - C \cos\theta_1 \cos\theta_2}{1 - C \cos\theta_1 \cos\theta_2}, \tag{3}$$

where B_i is equal to $\alpha_i P$, θ_i is the true polar angle between lepton i and its parent top quark and C is the so called anti-correlation factor, which is determined from the MC signal sample by fitting the two-dimensional distribution of both cosines. The denominator takes into account the already existing spin correlation in the signal Monte Carlo, while the numerator introduces the desired polarization of the top quark pairs. The polarization in the templates is constrained to a value of ± 0.3 for αP to avoid getting negative values for the cross section. It has been checked that the reweighting does not introduce a bias to the η-hypothesis of the reconstruction. Two different scenarios are considered for the production mechanism of the top-antitop pairs when introducing the polarization, one CP conserving (CPC) and one CP violating (CPV). For the CPC case, both quarks are polarized in the same way by choosing the same sign for B_1 and B_2, whereas in the CP violating case, the quarks will have opposite polarization. The likelihood fit is then applied by extracting the fraction f of positive polarization in our distribution and simultaneously the $t\bar{t}$ cross section to reduce normalization uncertainties (see Fig. 3). It is done by calculating the predicted number of events in each bin and channel and comparing it to the number of observed events. The maximized likelihood is the Poisson probability and is multiplied for each bin in the distribution and channel in the analysis. Systematics are considered by creating templates with $\pm 1\sigma$ variations for each source of systematic uncertainties. Correlations between systematics are considered by performing the fit simultaneously for one group of correlated systematics. 1000 pseudo experiments based on the templates are performed to reduce statistical effects on systematic uncertainties. Dominant sources of systematics are uncertainties from Jet Energy Scale, background normalization and signal modelling.



(a) CPC (b) CPV

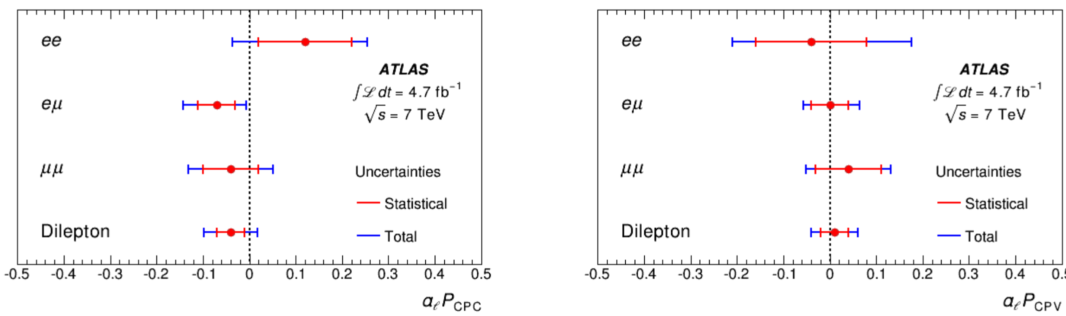
Figure 3: Fit of the *cos* θ distributions of positive and negative leptons for the two different production mechanisms CPC and CPV [7].

5 Results

The fit values for f have to be translated to αP first via $\alpha P = 0.3(2f - 1)$ [7]. For the result of the polarization measurement we get:

$$\begin{aligned} \alpha_l P_{CPC} &= -0.04 \pm 0.03(\text{stat}) \pm 0.05(\text{syst}) \\ \alpha_l P_{CPV} &= 0.01 \pm 0.03(\text{stat}) \pm 0.04(\text{syst}). \end{aligned}$$

Figure 4 shows the results for each channel and the combination separately.



(a) CPC (b) CPV

Figure 4: Results of the fit of $\alpha_l P$ for each channel and the combination for CPC and CPV production mechanisms [7]. All results are in agreement with the SM (dashed line).

The first measurement of the top quark polarization in dileptonic top-antitop quark events has been performed and is consistent with the Standard Model for both models considered. It was furthermore combined with the measurement in the single-lepton channel [7, 15].

References

[1] M. Muether *et al.* [Tevatron Electroweak Working Group and CDF and D0 Collaborations], arXiv:1305.3929 [hep-ex].

[2] I. I. Y. Bigi, Y. L. Dokshitzer, V. A. Khoze, J. H. Kuhn and P. M. Zerwas, Phys. Lett. B **181** (1986) 157.

[3] W. Bernreuther and Z. -G. Si, Phys. Lett. B **725** (2013) 1-3, 115, arXiv:1305.2066 [hep-ph].

[4] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **87** (2013) 011103, arXiv:1207.0364 [hep-ex].

[5] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **87** (2013) 092002, arXiv:1211.1003 [hep-ex].

[6] A. Brandenburg, Z. G. Si and P. Uwer, Phys. Lett. B **539** (2002) 235, hep-ph/0205023.

[7] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. Lett. **111** (2013) 232002, arXiv:1307.6511 [hep-ex].

[8] G. Aad *et al.* [ATLAS Collaboration], JINST **3** (2008) S08003.

[9] S. Frixione and B. R. Webber, JHEP **0206** (2002) 029, hep-ph/0204244.

[10] G. Aad *et al.* [ATLAS Collaboration], Eur. Phys. J. C **71** (2011) 1577, arXiv:1012.1792 [hep-ex].

[11] J. Beringer *et al.* [Particle Data Group], Phys. Rev. D **86** (2012) 010001.

[12] B. Abbott *et al.* [D0 Collaboration], Phys. Rev. Lett. **80** (1998) 2063, hep-ex/9706014.

[13] G. Aad *et al.* [ATLAS Collaboration], Eur. Phys. J. C **72** (2012) 1844, arXiv:1108.5602 [hep-ex].

[14] W. Bernreuther, A. Brandenburg, Z. G. Si and P. Uwer, Nucl. Phys. B **690** (2004) 81, hep-ph/0403035.

[15] S. Hamilton, these proceedings.