

# Top quark angular distributions at the LHC

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## Abstract.

Results from the CMS and ATLAS Collaborations are presented on angular distributions in top quark decays. The studies presented here are based on proton-proton collisions at a center of mass energy of 7 TeV collected by the two experiments at the LHC in 2011. The angular distributions of the top quark decay products are used to probe several fundamental properties of the top quark and its couplings. The polarization of produced top quarks is investigated as well as the correlation of the spin of pair-produced top and anti-top quarks. The polarization states of the  $W$ -boson originating from the decay of the top quark are determined and used to constrain possible contributions of new physics processes to the  $Wtb$  vertex.

## 1. Introduction

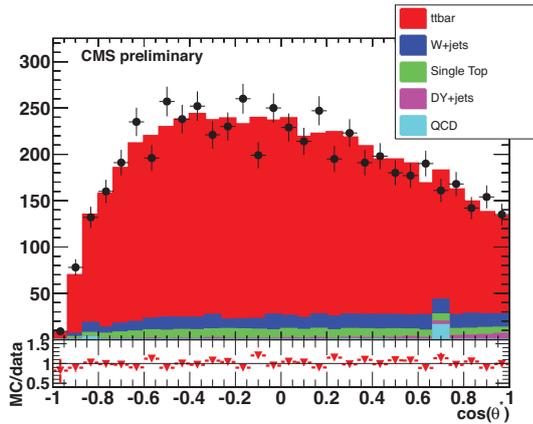
Since its discovery at the Tevatron in 1995 [1, 2] the top quark<sup>1</sup> has been the object of an intense program of study. The fact that it still provokes so much interest today is due to several reasons. To start with, the top quark is by far the heaviest known elementary particle and hence an ideal probe of the electro-weak symmetry breaking sector. The top quark can also be used to look for signs of new physics both in its production and decay, for example via searches for resonance production or flavor changing neutral currents. In addition the top quark decays before it has time to hadronize, thereby giving access to its properties for example through the angular distributions of its decay products. It is this latter characteristic that will be exploited here to study several fundamental properties of the top quark. Last but not least the decay products of the top quark provide a striking experimental signature. At the LHC, top quarks are mainly produced in pairs. They decay almost exclusively to a  $W$  boson and a bottom quark.  $t\bar{t}$  events are usually classified according to the decay mode of the two produced  $W$  bosons, which may decay either hadronically or into a charged lepton and a neutrino. The studies by the ATLAS [3] and CMS [4] Collaborations presented here make use of the single lepton and dilepton topologies, considering only electrons and muons, including those from leptonic  $\tau$  decays. The data used have been collected from proton-proton collisions at a center of mass energy of 7 TeV during 2011.

## 2. $W$ boson polarization

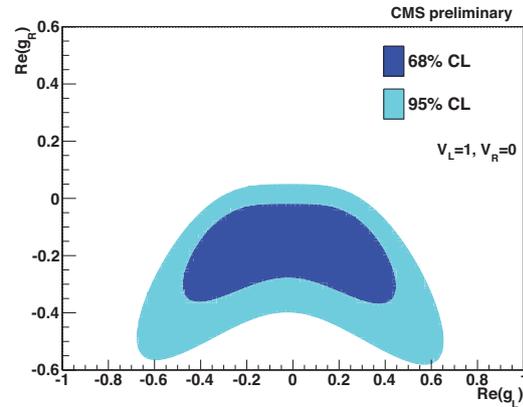
In the Standard Model, the top quark nearly always decays via a  $Wtb$  vertex defined by the electroweak interaction. The  $W$  boson is produced as a real particle in top decays and can hence assume longitudinal, left-handed or right-handed polarization states. The fractions of  $W$  bosons

<sup>1</sup> Unless explicitly stated, top quark refers to both the top and the anti-top quark.





**Figure 1.** The CMS [6]  $\cos \theta^*$  distribution, from where the  $W$  helicity fractions are obtained.

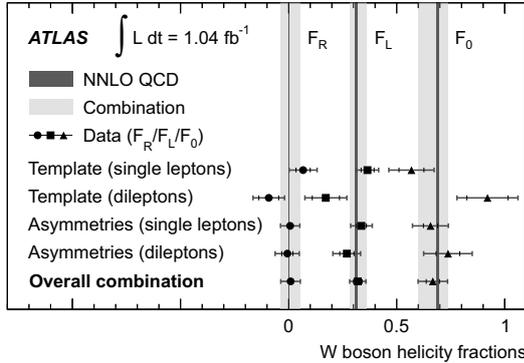


**Figure 2.** CMS [6] limits on the real components of the anomalous couplings  $g_L$ ,  $g_R$  at 68% and 95% confidence level.

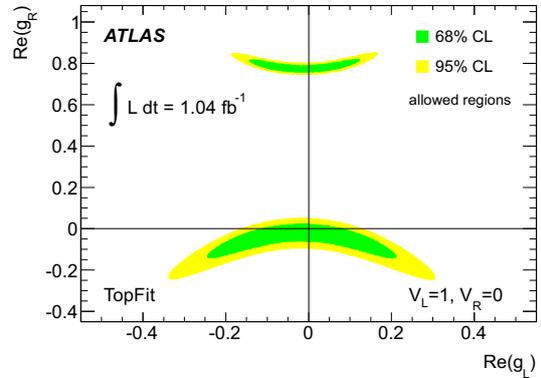
produced in each state are predicted in next-to-next-to-leading-order (NNLO) calculations as  $F_0 = 0.687 \pm 0.005$ ,  $F_L = 0.311 \pm 0.005$  and  $F_R = 0.0017 \pm 0.0001$  [5]. Experimentally the helicity fractions  $F_0$ ,  $F_R$ , and  $F_L$  can be determined from the angular distribution of the top decay products. In particular, ATLAS and CMS use the distribution of the angle  $\theta^*$  between the charged lepton in the  $W$  boson rest frame and the  $W$  boson momentum in the top quark rest frame, which can be expressed in terms of the helicity fractions as [5]:

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta^*} = \frac{3}{4}(1 - \cos^2 \theta^*)F_0 + \frac{3}{8}(1 - \cos \theta^*)^2 F_L + \frac{3}{8}(1 + \cos \theta^*)^2 F_R.$$

CMS [6] has determined the  $W$  boson helicity fractions in the single lepton muon channel using a data sample of  $2.2 \text{ fb}^{-1}$ . The  $\cos \theta^*$  distribution obtained from the data is shown in Figure 1, compared to the sum of simulated signal and background processes, normalized to the data luminosity. The  $t\bar{t}$  sample is additionally scaled by 10%. The main result is obtained by a template fit to the  $\cos \theta^*$  distribution using the three free parameters  $F_0$ ,  $F_L$ , and  $F_{t\bar{t}}$  ( $F_R$  is constrained to be  $1 - F_0 - F_L$ ).  $F_{t\bar{t}}$  is a normalization factor of the  $t\bar{t}$  component in the number of expected events entering the likelihood function. The helicity fractions obtained in this way are  $F_0 = 0.567 \pm 0.074(\text{stat.}) \pm 0.047(\text{syst.})$ ,  $F_L = 0.393 \pm 0.045(\text{stat.}) \pm 0.029(\text{syst.})$  and  $F_R = 0.040 \pm 0.035(\text{stat.}) \pm 0.044(\text{syst.})$ , in agreement with the Standard Model prediction. CMS has performed a further fit also constraining  $F_R$  to be zero, which leads to consistent results. The measurement of the helicity fractions can be used to set limits on new physics contributions to the  $Wtb$  vertex. Figure 2 shows the derived limits on the anomalous couplings  $g_L$  and  $g_R$  at 68% and 95% confidence level. ATLAS [7] has studied both electron and muon signatures in the single lepton and dilepton channel in a  $1.04 \text{ fb}^{-1}$  data sample to determine the helicity fractions. Both a template fit to the observed  $\cos \theta^*$  distributions and angular asymmetries as calculated from the  $\cos \theta^*$  distributions unfolded for detector effects are used. The asymmetries  $A_{\pm}$  are defined as the difference in numbers of events below and above a cutoff  $z = \pm(1 - 2^{2/3})$  in the  $\cos \theta^*$  distribution, normalized to the sum. The results for both methods are shown in Figure 3 in comparison to the NNLO QCD theory calculations [5]. Combining the separate results yields the main result of  $F_0 = 0.67 \pm 0.03(\text{stat.}) \pm 0.06(\text{syst.})$ ,  $F_L = 0.32 \pm 0.02(\text{stat.}) \pm 0.03(\text{syst.})$  and  $F_R = 0.01 \pm 0.01(\text{stat.}) \pm 0.04(\text{syst.})$ . Consistent results are obtained when fixing  $F_R = 0$ . The limits on the real parts of the  $Wtb$  vertex anomalous couplings  $g_L$  and  $g_R$  obtained by ATLAS using the helicity fractions are shown in Figure 4. The second minimum around  $\text{Re}(g_R) = 0.8$



**Figure 3.** Overview of the four ATLAS [7] measurements of the W boson helicity fractions and the combined values. The error bars correspond to the statistical and total uncertainties.

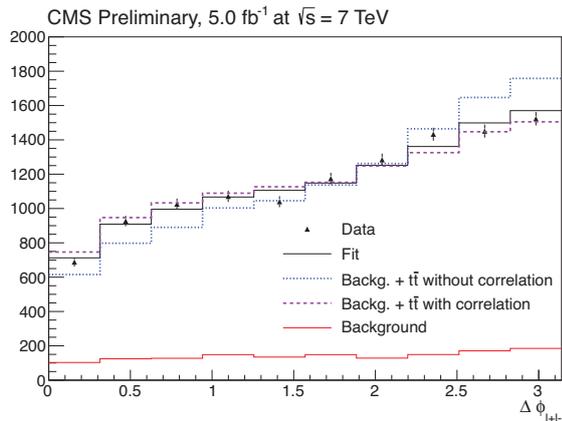


**Figure 4.** Allowed regions at 68% and 95% confidence level for the  $Wtb$  anomalous couplings  $g_L$  and  $g_R$  obtained by ATLAS [7].

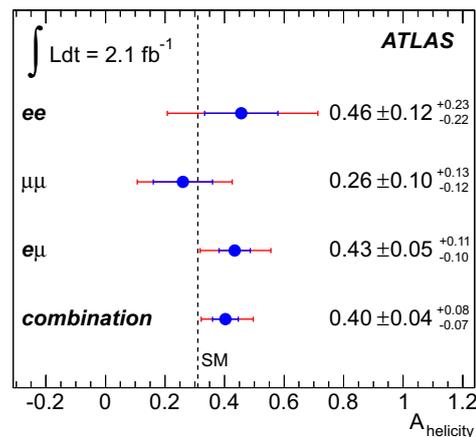
(also present, but not shown, in the CMS analysis) is not consistent with measurements of the single top cross section.

### 3. $t\bar{t}$ spin correlations

The polarization of pair-produced  $t$  and  $\bar{t}$  quarks is predicted to be very small, however their spins are predicted to be correlated. Since the top quarks decay before they can hadronize, this correlation is passed on to the decay products. For the studies presented here the correlation in azimuthal angle,  $\Delta\phi$ , between the two charged leptons in the dilepton channel is used to determine the amount of spin correlation present, as suggested in [8]. To extract the spin correlation from the  $\Delta\phi$  distribution, a template fit is employed, using templates of correlated

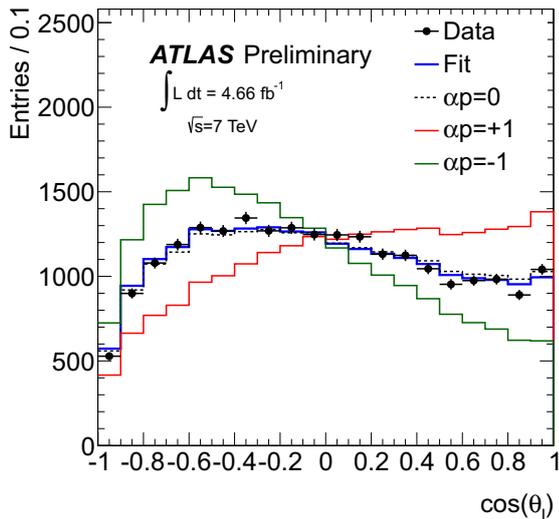


**Figure 5.** CMS [9] result of the spin correlation fit (solid line) performed on data (triangles) after the combination of the three channels. The data are also compared to the  $\Delta\phi_{l+l-}$  distribution of  $t\bar{t}$  events with and without spin correlation.

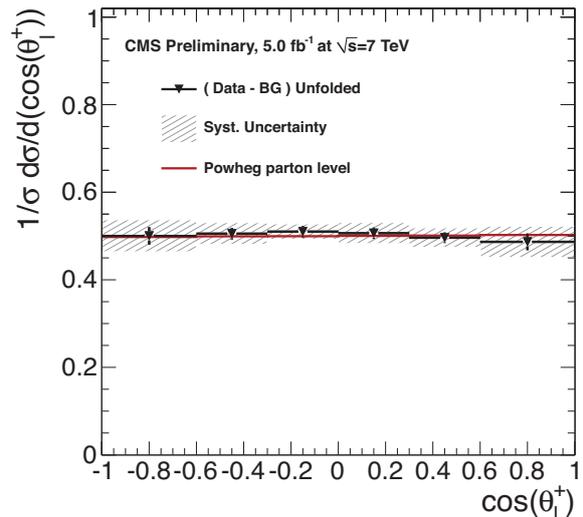


**Figure 6.** Value of  $A_{\text{helicity}}$  compared to the Standard Model prediction for the  $ee$ ,  $\mu\mu$  and  $e\mu$  channels and the combination, as obtained by ATLAS [11].

and uncorrelated samples, as well as background contributions. CMS [9] has analyzed a data sample of  $5 \text{ fb}^{-1}$  in the dilepton channel. Figure 5 shows the  $\Delta\phi$  distribution after combining the three dilepton channels, compared to the simulated sample with and without spin correlation. The data clearly prefer the slope with spin correlations, which is also evident in the fit result shown in the figure. Translating the fit result into a measured asymmetry in the helicity spin basis yields  $A_{\text{hel}}^{\text{meas}} = 0.24 \pm 0.02(\text{stat.}) \pm 0.08(\text{syst.})$ , in agreement with the Standard Model value of  $A_{\text{hel}}^{\text{SM}} = 0.31$  [10]. CMS [9] also studied asymmetries of numbers of events above and below certain cut-offs in angular distributions sensitive to spin correlation effects. These asymmetries, investigated before and after unfolding for detector effects, yield results consistent with those obtained from the template fit. ATLAS [11] has studied a data sample of  $2.1 \text{ fb}^{-1}$  in the dilepton channel. The template fit is performed for the  $ee$ ,  $\mu\mu$  and  $e\mu$  channels separately, and for all channels combined. The results are shown in Figure 6 and compared to the Standard Model value. The combined fit yields an asymmetry in the helicity spin basis of  $A_{\text{helicity}} = 0.40 \pm 0.04(\text{stat.}) \pm 0.07(\text{syst.})$ . The hypothesis of zero spin correlation is excluded by the ATLAS result with a significance of 5.1 standard deviations, amounting to the first observation of  $t\bar{t}$  spin correlations.



**Figure 7.** ATLAS [12] result of the top polarization fit to the electron channel compared to the data; the maximally polarized templates and the no polarization expectation are also shown.



**Figure 8.** CMS [13] background-subtracted and unfolded  $\cos\theta_l^+$  distribution used to determine the top quark polarization.

#### 4. Top polarization

The polarization of  $t$  and  $\bar{t}$  quarks can be obtained from the angular distribution of the decay products. The results presented here use leptonic decays of top quarks in the single lepton or dilepton decay channels of  $t\bar{t}$  events. In particular the distribution of the angle  $\theta_l$  between the lepton direction in the top rest frame and the top direction in the  $t\bar{t}$  centre of mass frame is obtained through performing a full event reconstruction. ATLAS [12] performs a template fit to the  $\cos\theta_l$  distribution, using fully positively and negatively polarized signal templates added to background expectations. The data set is obtained from a sample of  $4.66 \text{ fb}^{-1}$  in the single lepton channel. Figure 7 shows the  $\cos\theta_l$  distribution in the electron channel

together with the maximally polarized fit templates, the no polarization case, and the fit result. The combined result from electron and muon channels yields a degree of polarization of  $-0.060 \pm 0.018(\text{stat.}) \pm_{-0.064}^{+0.046}(\text{syst.})$ , consistent with no polarization and the Standard Model expectation. CMS [13] studies the  $\cos\theta_l$  distribution in dileptonic  $t\bar{t}$  decays in a data sample of  $5.0 \text{ fb}^{-1}$ . The reconstructed distribution is unfolded for detector effects and compared to the Standard Model expectation in Figure 8 for positively charged leptons. The final measured polarization value is  $-0.009 \pm 0.029(\text{stat.}) \pm 0.041(\text{syst.})$ , again consistent with no polarization and the Standard Model expectation.

## 5. Conclusion

The ATLAS and CMS Collaborations have used angular distributions of leptons from the single lepton and dilepton decay channels of  $t\bar{t}$  events to investigate several fundamental properties of the top quark. The data used in these studies have been collected from  $pp$  collisions at a center of mass energy of 7 TeV at the LHC. The structure of the  $Wtb$  vertex has been investigated via a determination of the helicity fractions of the  $W$  boson produced in the decay of the top quark. The polarization of the produced top quarks has been investigated as well as the spin correlation of top and anti-top quark for produced  $t\bar{t}$  pairs. All obtained results are consistent with the Standard Model expectations.

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