Measurements of Top Quark Properties at the LHC

A. Lister on behalf of the ATLAS and CMS Collaborations
Section de Physique, Université de Genève, Geneva, Switzerland

A total of 20 measurements carried out by the ATLAS and CMS Collaborations of the properties of top quarks were presented. These were measurements of the top quark charge, of the spin correlation between the top and the anti-top quark, of the charge asymmetry, of the polarisation of the W-boson, the measurement of the hadronic activity in the central rapidity region in $t\bar{t}$ events, and the measurement of the branching ratio of top quarks. Some direct searches for new physics were also presented: searches for fourth generation top-like and bottom-like quarks as well as more exotic T quarks with anomalous decay modes.

1 Properties of the Top Quark

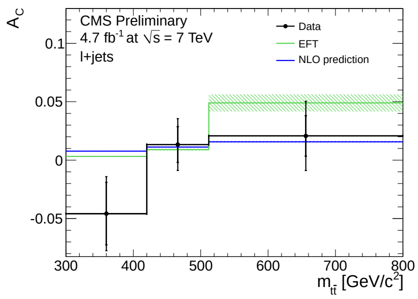
Many measurement of the properties of the top quark were presented. The measurements all used data from the 2011 LHC run, using integrated luminosities ranging from 0.7 to 4.6 fb^{-1}, the latter corresponding to the full 2011 data sample.

Top charge Both the CMS [?] and ATLAS [?] Collaborations have excluded at more than 5σ the top quark having a charge 4/3e, in favour of the standard model (SM) prediction of 2/3e. The charge of the W is identified through the charge of the lepton; the charge of the b-jet is determined from the presence of a soft lepton inside the jet.

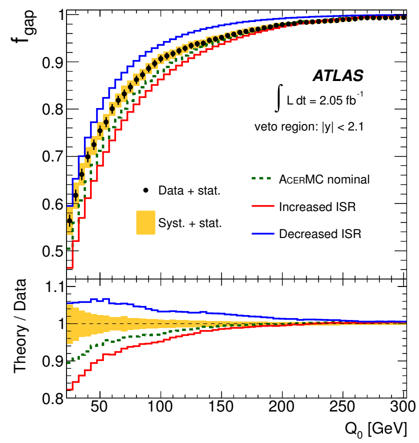
Spin correlations The measurement of the spin correlation between the top and the anti-top quark is sensitive to the fact that the life-time of the top quark is so short that it decays before it hadronises and thus for $t\bar{t}$ events, one expects the spin structure to be preserved. In top decays where both W-bosons decay leptonically, the angular separation between the two leptons is sensitive to the presence of such correlations. The ATLAS Collaboration [?] is able to exclude at more than 3 σ the scenario with no spin correlations, and measures a degree of spin correlation compatible with that predicted by the SM.

Charge asymmetry Unlike the $p\bar{p}$ collisions from the Tevatron, the LHC pp collisions cannot give a direct forward-backward asymmetry in the production of top quark pairs. Yet owing to the Parton Distribution Functions being different for quarks and anti-quarks, the difference in rapidity (y) distributions of the top and anti-top can be used to measure a form of asymmetry; indeed the top quark spectrum in y is expected to be slightly broader than for that of the anti-top. By using the difference in absolute rapidity between the top and anti-top ($\Delta|y| = |y_t| - |y_{\bar{t}}|$) one can define an asymmetry

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}. \quad (1)$$



(a) Corrected asymmetry as a function of $m_{t\bar{t}}$. The measured values are compared to NLO calculations for the SM and to predictions from an effective field theory. The error bars on the differential asymmetry values indicate the staistitcal and systematic uncertainties



(b) The measured gap fraction as a function of Q_0 for $|y| < 2.1$ is compared with the prediction from the AcerMC generator, where different settings of the Pythia parton shower parameters are used to produce samples with nominal, increased and decreased initial state radiation (ISR).

Predictions from the MC@NLO generator are at the level of 0.006 ± 0.002. The measurement of a larger asymmetry would be an indication of new physics. Both the ATLAS [?] and CMS [?] Collaborations have studied this asymmetry in a variety of different kinematic regions. Both collaborations used the lepton+jets decay mode where one W decays leptonically and the other hadronically and both relied on the identification of at least one heavy flavour (b-tagged) jet. The measurements are corrected for detector and acceptance effects. The overall measurements of A_C are compatible with zero; ATLAS measures an overall charge asymmetry of $A_C = -0.018 \pm 0.028(stat) \pm 0.023(syst)$, while CMS measures a value of $A_C = 0.004 \pm 0.010(stat) \pm 0.012(syst)$. This asymmetry was also measured for different kinematic regions: for different values of the $t\bar{t}$ invariant mass (ATLAS and CMS) and as a function of the transverse momentum (p_T) of the $t\bar{t}$ system (CMS). The distribution as a function of the $t\bar{t}$ invariant mass from the CMS Collaboration is shown in Fig. **??**. These results disfavour many of the models developed to account for the forward-backward asymmetry observed at the Tevatron [?,?].

W boson polarisation In order the measure the three components of the polarisation of the W-boson, the distribution of the $\cos\theta^*$ is studied. This angle represents the angle between the lepton momentum in the W rest-frame and the momentum of the W in the top rest-frame. After subtracting the background distributions, the observed $\cos\theta^*$ distribution is corrected to particle-level. The resulting distribution is then fitted to templates of each of the three polarization components, with the constraint that the total fraction has to be unity. The SM predicts contribution close to zero for the right-handed polarisation, about 31% left-handed and 69% longitudinal polarisation. Both the ATLAS [?] and CMS [?] results are compatible with the SM predictions. The right handed polarisation component, F_R, is predicted to be 0.0017 ± 0.0001 at Next to Next to Leading Order, and is measured to be $0.09 \pm 0.04(stat) \pm 0.09(syst)$ and $0.040 \pm 0.035(stat) \pm 0.044(syst)$ by the ATLAS and CMS Collaborations, respectively. These results are then used to place stringent limits on anomalous couplings, described by an effective field theory, given that the scale of new physics is larger than the observable region.

$t\bar{t}$ + jet veto This measurement looks at the fraction of events that do not contain jet activity above a certain threshold in the central region. Two different types of thresholds are measured, either on the leading p_T emission from $t\bar{t}$ (Q_0), or on the sum of all emissions in that region (Q_{sum}). ATLAS [?] uses a high purity $t\bar{t}$ sample where both W-bosons decay leptonically and at least two identified heavy flavour jets. These quantities are measured in four different $|y|$ regions as a function of the Q variable, after correcting for detector effects. This measurement is extremely sensitive to the initial state radiation and can be used to constrain some parameters of Monte Carlo generators, in particular related to the parton shower. Figure **??** shows this rapidity gap fraction as a function of Q_0 for $|y| < 2.1$ in data compared to AcerMC generator with nominal and varied parton shower parameters. The data is represented as closed (black) circles with statistical uncertainties. The yellow band is the total experimental uncertainty on the data (statistical and systematic). The theoretical predictions are shown as solid and dashed coloured lines [a].

Top branching ratios In the SM, the top is expected to decay ∼100% of the time to a W-boson and a b-quark. Thus the observation of any other decay mode would be a sign of new physics. Using data in the dilepton channel and looking at the multiplicity of the identified heavy flavour jets, the CMS Collaboration was able to measure the branching ratio to Wb to a W-boson and any quark (Wq) to be 0.98 ± 0.04 and place the 95% confidence level around 0.85 [?].

Flavour changing neutral currents In addition to looking for anomalous decays to a W boson and a non-b-quark, one can look for flavour changing neutral current decay modes $t \rightarrow qZ$. Many models of new physics predict measurable branching ratios in this decay mode. Results from the ATLAS [?] and CMS [?] Collaborations have put upper limits on this fraction at 1.1% and 0.34%, respectively. In these analyses, events with three leptons are considered, where two of the leptons should be compatible with a Z-boson and the other originate from the other top quark that decays to Wb.

One can also search for flavour changing neutral currents, not in the decay mode, but in the production mode. The ATLAS Collaboration looked for production modes where a coupling between a gluon, a top quark and a light quark could exist [?]. These signatures would be similar to single top production but with different kinematics. In order to separate this new signature from the SM backgrounds, a neutral network is used. Stringent limits are placed on the maximum allowed branching ratios of top to ug and cg at the level of $5.7 \cdot 10^{-5}$ and $2.7 \cdot 10^{-4}$, respectively.

2 Searches for New Physics Using Top Quarks

While most of the measurements of the properties of the top quark can be used to place limits on anomalous behaviour and thus limits on the presence of new physics, direct searches for new physics resulting in signatures containing or resembling those of SM top quarks can be carried out.

Fourth generation top-like quarks Results for fourth generation top-like quarks were presented in both the lepton+jets and the dilepton channels [?,?,?]; in the lepton+jets analyses, there is an explicit requirement on the decay mode $t' \rightarrow Wb$, while for the ATLAS dilepton analysis, the more generic decay mode to Wq is considered. The mass of the top-quarks are reconstructed and one looks for excesses in the tails of this distribution, where the proposed t' would be expected to be seen. No evidence for such quarks is found; lower limits on the t' mass between 350 and 560 GeV are obtained.

[a] As this is an inclusive quantity, representing the fraction of events with activity above a certain threshold, the points are highly correlated.

Fourth generation bottom-like quarks Searches are also carried out for fourth generation bottom-like quarks (b') decaying to a W-boson and a top quark. Such events would have a very high multiplicity; thus in order to reduce the contribution from the SM background one can select same-sign dilepton events, tri-lepton events or lepton+jet events with semi-boosted W-bosons. In these analyses [?,?,?], lower limits on the mass of the b' have been set between 450 and 495 GeV. One of the ATLAS results can also be interpreted in terms of anomalous production of quarks and is able to exclude most of the phase-space of the Z' hypothesis used to explain the Tevatron A_{fb} measurement for Z' masses from 0.1 to 1 TeV.

$\mathbf{t\bar{t}}$ events with large missing transverse energy In some extensions of fourth generation-like quarks, one can have massive top-like quarks decaying to a top quark and a weakly interacting particle, $T \to tA_0$. The pair-production of such quarks will result in signatures similar to those of $t\bar{t}$ events but with additional missing transverse energy. One can thus look for the presence of such events in the tails of the missing transverse energy distribution of events in the lepton+jets decay mode. Limits are placed by the ATLAS collaboration in the plane of the mass of the T and the A_0 particles, with limits extending out to 420 and 150 GeV, respectively [?].

Flavour changing neutral current in fourth-generation-like top Another possible signature for these T quarks would be flavour changing neutral current decays $T \to Zt$ resulting in $t\bar{t}$-like signatures with two extra Z-bosons. By reconstructing events with three or more leptons and requiring two opposite sign leptons to form a Z-peak, the CMS Collaboration was able to place limits on the mass of the T up to 475 GeV [?].

References

1. The CMS Collaboration, CMS-PAS-TOP-11-031.
2. The ATLAS Collaboration, ATLAS-CONF-2011-141.
3. The ATLAS Collaboration, Phys. Rev. Lett. **108**, 212001 (2012).
4. The ATLAS Collaboration, Accepted by EPJC [arXiv:1203.4211].
5. The CMS Collaboration, CMS-PAS-TOP-11-030.
6. The CDF Collaboration, Phys. Rev. D **83** 112003 (2011) .
7. The D0 Collaboration, Phys. Rev. D **84**, 112005 (2011).
8. The ATLAS Collaboration, Accepted by JHEP [arXiv:1205.2484].
9. The CMS Collaboration, CMS-PAS-TOP-11-020.
10. The ATLAS Collaboration, Accepted by EPJC [arXiv:1203.5015].
11. The CMS Collaboration, CMS-PAS-TOP-11-029.
12. The ATLAS Collaboration, Submitted to JHEP [arXiv:1206.0257].
13. The CMS Collaboration, CMS-PAS-TOP-11-028.
14. The ATLAS Collaboration, Phys. Lett. **B712** (2012) 351-369 [arXiv:1203.0529].
15. The ATLAS Collaboration, Accepted by Phys. Rev. Lett. [arXiv:1202.3076].
16. The CMS Collaboration, CMS-PAS-EXO-11-099.
17. The ATLAS Collaboration, Submitted to Phys. Ref. D. [arXiv:1202.3389].
18. The ATLAS Collaboration, Accepted by Phys. Rev. Lett. [arXiv:1202.6540].
19. The ATLAS Collaboration, Submitted to JHEP [arXiv:1202.5520].
20. The CMS Collaboration, Submitted to JHEP [arXiv:1204.1088].
21. The ATLAS Collaboration,*Phys. Rev. Lett.* **108**, 041805 (2012).
22. The CMS Collaboration, *Phys. Rev. Lett.* **107**, 271802 (2011).