Measurement of the top quark charge in the ATLAS experiment

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Introduction

Discovered in 1995 by CDF and D0 Experiments, the top quark is the heaviest known elementary particle. The possibility that an exotic quark with charge -4/3 (in units of the electron charge) is produced instead of the Standard Model top quark was recently excluded by the CDF Experiment at 95% C.L.. Here a similar ATLAS measurement with 0.70 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 7 TeV is presented.

- Two scenarios are considered:
  - the SM top quark decaying as $t^{2/3} \to W^{+1} + b^{-1/3}$
  - an exotic heavy quark of the same mass but with charge equal to -4/3 decaying as $T^{-4/3} \to W^{-1} + b^{-1/3}$
- The decay products of a pair of such exotic quarks are identical to those of $t\bar{t}$
- To exclude the exotic quark one needs to
  - correctly pair the b-jet and W boson
  - measure the charges of the b-jet and W boson
- The two analyses presented here use different approaches to these tasks.

Methods

To measure the top quark charge one needs to determine the charge of both the W boson and b-quark. While the charge of the W boson can be determined through its leptonic decay, the b-quark charge is not directly measurable as the b-quark hadronisation process results in a jet of hadrons (b-jet). It is possible however to establish a correlation between the charge of the b-quark and a weighted sum of the electric charges of the particles belonging to the b-jet (track charge weighting technique). One can also use semileptonic B-hadron decays ($b \to c, u + \ell + \nu_\ell$). In this case the sign of the lepton arising from the semileptonic decay defines the sign of the b-quark charge (soft lepton technique).

Event selection

The $t\bar{t}$ candidates in the electron or muon plus jets final states were first selected with the electron or muon trigger with a transverse energy (E_T) threshold of 20 GeV for electrons and 18 GeV for muons. There had to be exactly one isolated lepton (electron or muon) with p_T exceeding 25 GeV (electron) or 20 GeV (muon) in the event and this lepton had to be the same as the trigger lepton. Jets were reconstructed in candidate events using the standard ATLAS implementation of the so-called "anti-kt" algorithm with jet separation parameter R = 0.4. At least four jets with transverse momentum p_T > 25 GeV and within pseudorapidity range |η| <2.5 were required. E_T^{miss} had to exceed 35 GeV for the events with electrons, and 20 GeV for the events with muons. To ensure a good event quality, a primary vertex containing at least five charged particles was required, and events containing jets in poorly instrumented regions with transverse momentum exceeding 20 GeV were removed. The transverse mass of the leptonically decaying W boson in the event was reconstructed as $m_T(W)=\sqrt{2p_T^l p_T^\nu(1-\cos(\varphi^l-\varphi^\nu))}$, where the measured E_T^{miss} provided information on the transverse momentum and angle of the neutrino. For the events with electrons this mass had to exceed 25 GeV, while the sum of this mass and E_T^{miss} had to exceed 60 GeV for the events with muons. Finally, at least one jet was required to be b-tagged by a well reconstructed secondary vertex. This common selection was followed by requirements specific for each of the two methods used to reconstruct the charge of b-quarks. For the track charge weighting method, the presence of a second b-tagged jet was required. Each of the two b-tagged jets had to contain at least two well reconstructed charged particles with transverse momentum above 1 GeV/c within the pseudorapidity region |η| <2.5. For the soft lepton method, a muon with transverse momentum greater than 4 GeV had to be found within a cone of radius $\Delta R=\sqrt{\Delta\eta^2+\Delta\varphi^2}$ < 0.4 from a jet axis.

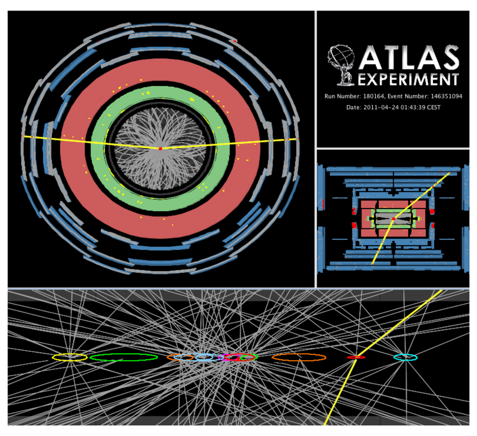


Figure: A typical ATLAS environment in 2011 with high pileup. Top quarks are produced in such collisions. In the event shown one observes 11 reconstructed vertices and a Z boson, decaying into a pair of muons, produced in one of them .

Method I: Weighted charges of tracks in b-jets

To determine the top quark charge one needs to know:

- The W boson charge → obtained from its leptonic decay.
- The average b-jet charge → found through b-jet track charges:

$$Q_{bjet} = \frac{\sum_i q_i |\vec{j}\cdot\vec{p}_i|^\kappa}{\sum_i |\vec{j}\cdot\vec{p}_i|^\kappa}$$

q_i – ith particle charge, $\vec{p}_i$ – ith particle momentum, $\vec{j}$ – b-jet direction, κ – an exponent (0.5)

- A correct pairing of the lepton and b-jet (should be from the same top quark) → only the events with the b-jets that satisfying lepton-b-jet invariant mass criterion were accepted:

$$m(l,b_{jet}^{(1,2)}) < m_{cr} \;\;\&\;\; m(l,b_{jet}^{(2,1)}) > m_{cr}$$

  - The optimal value for the pairing mass cut was found to be m_{cr} = 155 GeV.
  - Invariant mass criterion used the two highest transverse momentum b-tagged jets in the event.
  - To distinguish between the Standard Model and exotic model scenarios the combined charge, Q_{comb}, was used:

$$Q_{comb} = Q_{bjet} * Q_\ell$$

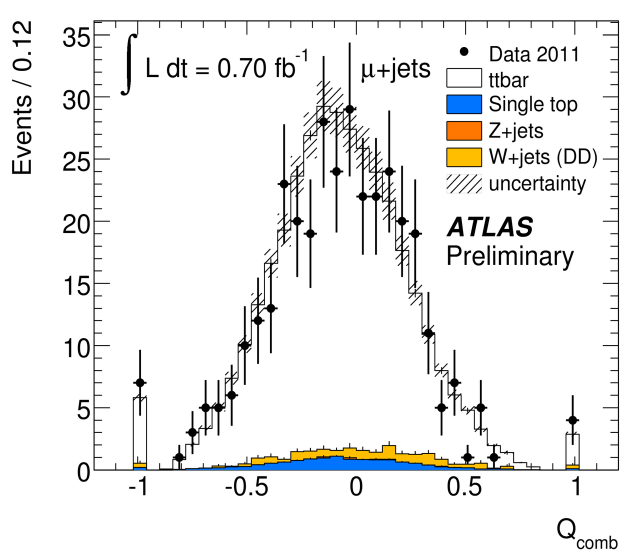
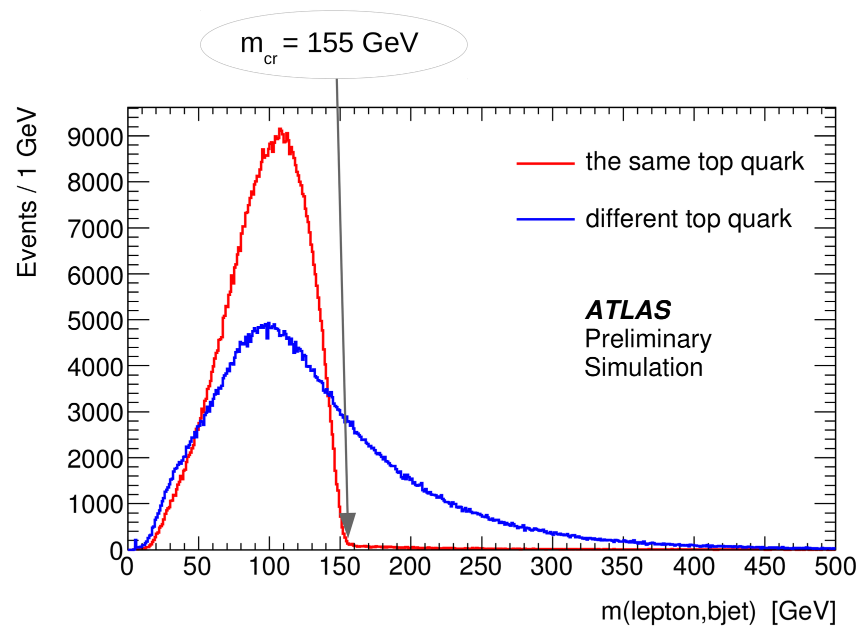


Figure: Comparison of the combined b-jet charge Q_{comb} in the muon (top) and the electron (bottom) final states in the data with the Standard Model expectations for signal and background events. The top quark with Q = - 4/3e would result in a distribution reflected with respect to the Q_{comb} = 0 axis, thus with a positive mean.



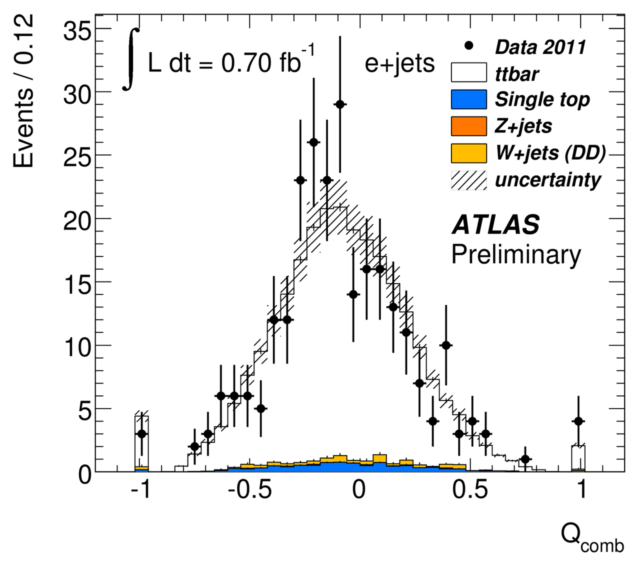


Figure: Lepton - b-jet invariant mass spectra for the lepton and b-jet from the same top quark (red line) and for those originating in different top quarks (blue line).

Method II: Semileptonic decay of b hadrons

- Kinematic Likelihood Fitter (KLFitter) is applied to choose the b-jet coming from the leptonically decaying top
  - It assigns one of the the four highest transverse momentum jets (b-tagged or not) to be from the b-quark which comes from the same top as the leptonically decaying W boson (leptonic b-quark)
  - The efficiency of leptonic b-quark matching is 68% for events with at least one b-tagged jet
- b-jet charge is measured via the charge of a soft muon coming from semileptonic decays of b hadrons

- B hadron (mostly B^0 and $B^\pm$) is always present in a b-jet
- In about 11% of cases B hadrons decay to μ + ν + X
- Muons from B decays have charge of the same sign as the b-quark (except when B^0 oscillations take place)
- Another source of muons in b-jets are charmed hadrons
  - BR (b → c → μ + ν + X) ≈ 10%
  - These muons have mostly charge opposite to the b-quark charge
- Muons in jets can also be from decays of lighter hadrons
  - Not as often as from B or C

Thus the muon in b-jets (soft muon) does not necessarily have the same sign of the charge as b-quark which initiated the jet.

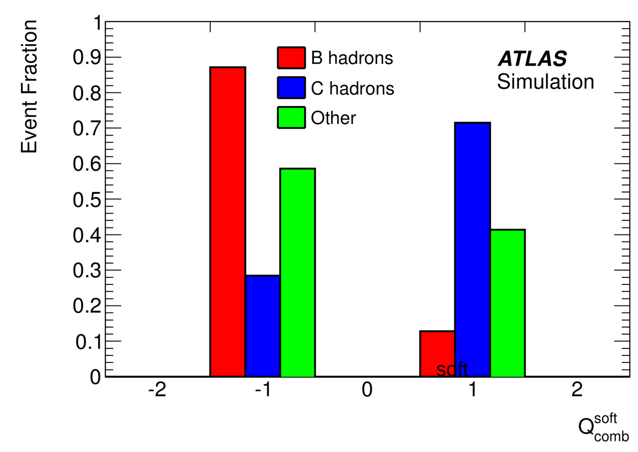


Figure: The distribution of $Q_{comb}^{soft} = Q_{soft\mu} \times sign(-Q_{bquark})$. The distributions for each hadron flavour are normalised to 1.

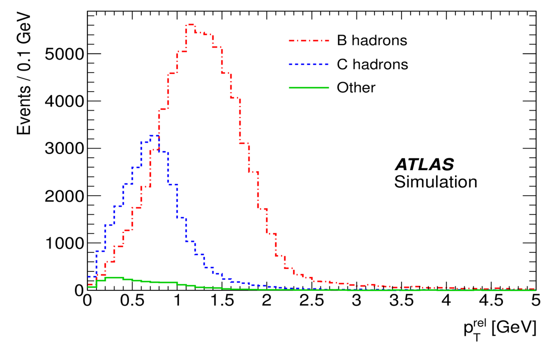
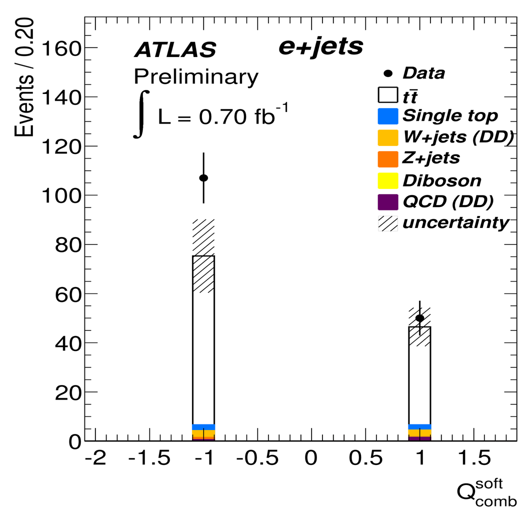


Figure: The p_T of the soft muon with respect to the b-jet direction, p_T^{rel} for soft muons originating from b hadrons, c hadrons and light hadrons (other).



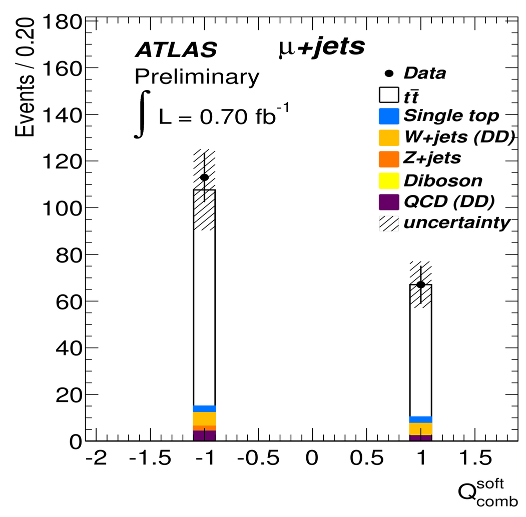


Figure: Distribution of the combined charge Q_{comb}^{soft} in muon + jets (left-hand side) and electron + jets (right-hand side) events in the data and Standard Model expectation. When compared to the SM top quark, the top quark with Q = -4/3e would result in the bin contents of the Q_{comb}^{soft} = 1 exchanged with that of Q_{comb}^{soft} = - 1. (DD) denotes the background contribution estimated with data-driven methods.

Results

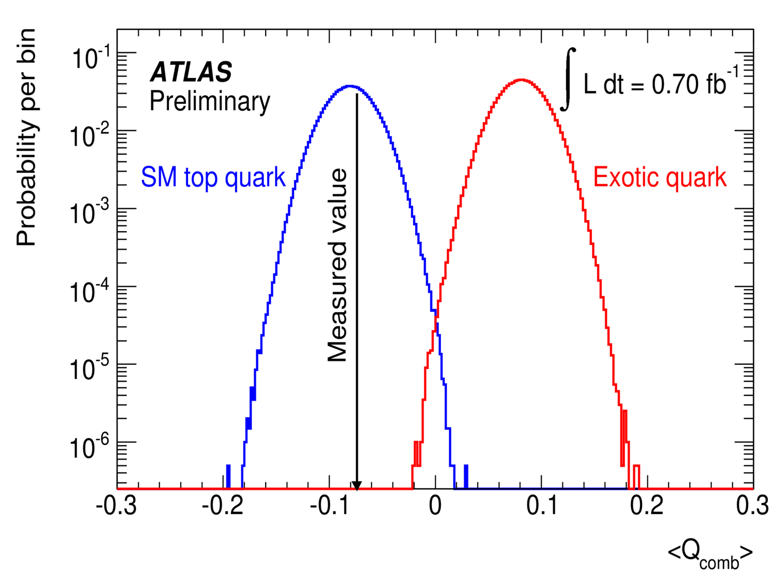
Model	$< Q_{comb} >$		
	e + jets	μ + jets	combined
SM	-0.084 ± 0.020 (stat)	-0.081 ± 0.018 (stat)	-0.082 ± 0.013 (stat)
Exotic	+0.085 ± 0.019 (stat)	+0.088 ± 0.018 (stat)	+0.083 ± 0.013 (stat)
Measured	-0.088 ± 0.022	-0.078 ± 0.020	-0.082 ± 0.015

Model	$< Q_{comb}^{soft} >$		
	e + jets	μ + jets	combined
SM	-0.237 ± 0.016 (stat)	-0.232 ± 0.015 (stat)	-0.234 ± 0.011 (stat)
Exotic	+0.241 ± 0.016 (stat)	+0.180 ± 0.015 (stat)	+0.209 ± 0.011 (stat)
Measured	-0.36 ± 0.09	-0.26 ± 0.10	-0.31 ± 0.07

Table: The measured and the expected average values of Q_{comb} and Q_{comb}^{soft}. The expected values are for the Standard Model top and the exotic quark scenarios. The quoted errors are statistical only. The errors on the measured values include both the statistical and the systematic uncertainties.

Source	$< Q_{comb} >$ (%)		$< Q_{comb}^{soft} >$ (%)	
	e + jets	μ + jets	e + jets	μ + jets
ISR/FSR soft	13.8	11.0	15	24
Other $t\bar{t}$ modeling uncertainties	2.1	1.6	7	10
W+jets uncertainties	1.2	1.9	1.8	5.5
QCD uncertainties	0.4	1.6	4.0	1.0
Other SM background modeling uncertainties	2.0	1.0	< 1	1.6
Jet/E_T^{miss} systematics	7.2	7.6	5	7.5
Lepton systematics	2.9	4.1	2	1.5
b-tagging systematics	1.1	< 1	1	< 1
Total uncertainty (%)	16.2	14.4	18	27

Table: Systematic uncertainties for < Q_{comb} > and < Q_{comb}^{soft} >. The total uncertainty was calculated by adding the individual ones in quadrature. The estimation of some of the systematic uncertainties suffers from a small number of simulated events. The statistical error is in these cases conservatively included in the systematic effect estimation.



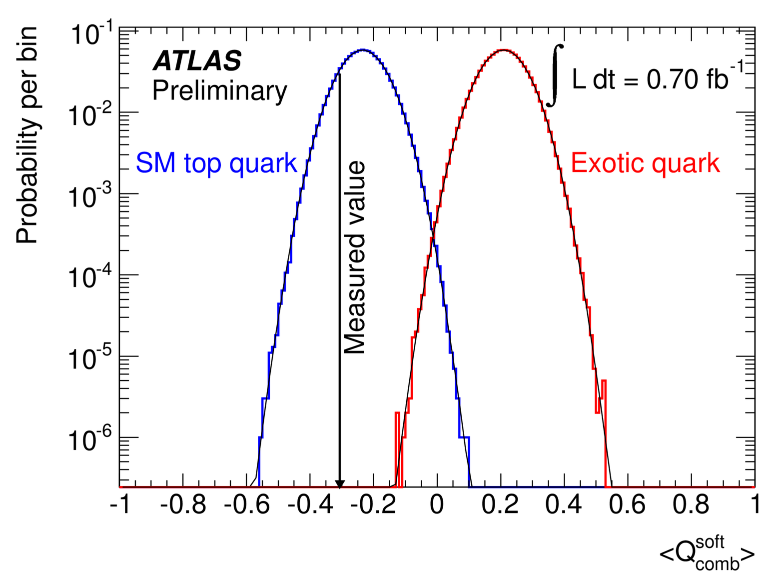


Figure: The expected < Q_{comb} > and < Q_{comb}^{soft} > obtained from the large number of pseudo-experiments combining the electron+jets and the muon+jets channels in the Standard Model (blue) and the exotic (red) scenarios. The measured values from the data are marked with arrows.

Isolated-lepton+jets final states in 0.7 fb^{-1} of data accumulated in the ATLAS Experiment at center-of-mass energy 7 TeV have been used to exclude a possibility that an exotic quark state with charge -4/3 is produced instead of the SM top quark. The exotic scenario is found to be excluded at more than 5σ C.L..

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