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Measurement of the top-quark charge in the ATLAS experiment

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Summary. — A measurement of the top quark charge using the lepton+jets final state resulting from $t\bar{t}$ pair production is presented, using data from the ATLAS detector at the LHC. The results were obtained using proton-proton collision data at $\sqrt{s} = 7\,\text{TeV}$ corresponding to an integrated luminosity of $0.70\,\text{fb}^{-1}$. The hypothesis that the top quark is instead an exotic quark with charge $-4/3e$ is excluded at more than five standard deviations.

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1. – Introduction

In this note, a measurement of the top quark charge at the Large Hadron Collider with $0.70\,\text{fb}^{-1}$ of proton-proton collision data collected by the ATLAS experiment [1] at $\sqrt{s} = 7\,\text{TeV}$ is presented. The top-quark charge measurement is based on reconstructing the charges of the top quark decay products. Studies on top-quark charge were done by the DØ Collaboration [2] and recently by the CDF experiment [3]. The dominant decay channel of the top quark, $t \to W^+b(\bar{t} \to W^-\bar{b})$, has a W-boson and a b-quark in the final state. 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 hadronic particles (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). Semileptonic B-hadron decays ($b \to c, u + W^-, W^- \to \ell^- + \bar{\nu}_\ell$) can also be used. In this case the sign of the lepton arising from the semileptonic decay defines the sign of the b-quark charge (soft lepton technique). In the soft lepton approach, the presence of B-oscillations and semileptonic decays of c quarks dilutes the correlation between the apparent charge of the b-jet and the charge of the initial b-quark. B-oscillations also affect the track charge weighting technique.

2. – 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-k_t" algorithm with jet separation parameter $R = 0.4$. At least four jets with transverse momentum $p_{\mathrm{T}} > 25$ GeV and within pseudorapidity range $|\eta| < 2.5$ were required. $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 $m_T(W) = \sqrt{2p_T^l p_T^\nu(1 - \cos(\phi^l - \phi^\nu))}$, where the measured $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 with a weight exceeding 5.85 [4]. 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 within the pseudorapidity region $|\eta| < 2.5$. For the soft lepton method, a muon with transverse momentum greater than 4 GeV had to be found within a cone of radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$ from any jet axis.

3. – Methods of top quark charge determination

3˙1. *Weighting procedure for the b-jet charge and the lepton – b-jet pairing algorithm.* – To determine the b-jet charge a weighting technique was employed in which the b-jet charge is defined as a weighted sum of the b-jet track charges:

$$Q_{b\text{-jet}} = \frac{\sum_i q_i |\vec{j} \cdot \vec{p}_i|^\kappa}{\sum_i |\vec{j} \cdot \vec{p}_i|^\kappa}, \tag{1}$$

where $q_i(p_i)$ is the charge (momentum) of the i-th track, $\vec{j}$ is the b-jet axis direction and $\kappa = 0.5$ is a parameter optimized for the best separation of b- and $\bar{b}$-jets. The decision to use at most the ten highest p_{T} charged particle tracks with $p_{\mathrm{T}} > 1$ GeV pointing to a b-jet within a cone of $\Delta R < 0.25$ follows from the optimization.

To distinguish between the Standard Model and exotic model scenarios was used the variable combined charge $Q_{comb} = Q_{b\text{-jet}} \cdot Q_\ell$, where $Q_{b\text{-jet}}$ and Q_ℓ are, respectively, the b-jet charge as measured in eq. (1) and the lepton charge, where the b-jet and lepton ℓ were assumed to come from the same top quark. The lepton and b-jet pairing was performed using the invariant mass distribution of the lepton and the b-tagged jet, $m(\ell, b\text{-jet})$. If the assignment is correct, $m(\ell, b\text{-jet})$ cannot exceed the top quark mass. Only the events satisfying the matching condition $((m(\ell, b\text{-jet}_1) < m_{cr} \wedge m(\ell, b\text{-jet}_2) > m_{cr}) \vee (m(\ell, b\text{-jet}_2) < m_{cr} \wedge m(\ell, b\text{-jet}_1) > m_{cr}))$ were accepted, and the b-jet from the pair with

TABLE I. – *Comparison of the data and Standard Model simulation (MC) for the product of b-jet and isolated lepton charges, $\langle Q_{comb} \rangle$, and for the average value of the product of the soft muon and isolated lepton charges, $\langle Q^{soft}_{comb} \rangle$. The errors on the simulation prediction are statistical only.*

channel	$\langle Q_{comb} \rangle$	
	Data	SM (MC)
e + jets	-0.088 ± 0.020 (stat) ± 0.012 (syst)	-0.084 ± 0.020
μ +jets	-0.078 ± 0.018 (stat) ± 0.010 (syst)	-0.081 ± 0.018
e/μ + jets	-0.082 ± 0.013 (stat) ± 0.011 (syst)	-0.082 ± 0.013

channel	$\langle Q^{soft}_{comb} \rangle$	
	Data	SM (MC)
e + jets	-0.36 ± 0.07 (stat) ± 0.04 (syst)	-0.237 ± 0.016
μ + jets	-0.26 ± 0.07 (stat) ± 0.06 (syst)	-0.232 ± 0.015
e/μ + jets	-0.31 ± 0.05 (stat) ± 0.04 (syst)	-0.234 ± 0.011

mass below m_{cr} was matched with the lepton. The optimal value for the pairing mass cut was found to be $m_{cr} = 155$ GeV.

3˙2. *Semileptonic decays of B-hadrons and the lepton – b-jet pairing with the KLFitter*. – The semileptonic decay branching ratio of B-hadrons to muons is $BR(b \to \mu+\nu+X) \approx 11\%$. The muon from such a decay will be identified as a non-isolated muon inside the corresponding b-jet, and its charge has the same sign as the charge of the b-quark that produced the jet. However not all non-isolated muons in b-jets are products of B-hadron direct decays. They may also originate from sequential decays of B-hadrons, when a B-hadron decays to a D-hadron (containing a charm quark), which in turn decays semileptonically. The branching ratio of this decay chain is $BR(b \to c \to \mu + \nu + X) \approx 10\%$. These muons usually have the opposite charge to the initial b quark charge and thus they contaminate the selected signal sample. Leptons having opposite charge to the initial b-quark may also come from neutral B-meson oscillations.

A likelihood based method (Kinematic Likelihood Fitter, KLFitter) was used to determine the correct event topology, specifically the correct pairing of a jet (b-tagged or not) with the isolated lepton stemming from the semileptonic W decay. The KLFitter used the four highest transverse momentum jets in the event.

4. – Results

Good agreement with the Standard Model prediction is observed in both cases. The values of $\langle Q^{soft}_{comb} \rangle$ (soft muon method) and $\langle Q_{comb} \rangle$ (track charge weighting method) are shown in table I. The data are consistent with the Standard Model prediction. The measured $\langle Q_{comb} \rangle$ and $\langle Q^{soft}_{comb} \rangle$ are each more than 4.5σ away from the values expected from the exotic quark hypothesis when the two lepton flavors are treated separately. If electron and muon channels are combined, the exotic quark scenario is excluded at a confidence level greater than 5σ with either of the b-quark charge measurement methods. Dominant systematic uncertainties for both methods are ISR/FSR and Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$. For the soft muon method, the $t\bar{t}$ modeling is also important.

5. – Conclusion

Isolated-lepton+jets final states in $0.70\,\mathrm{fb}^{-1}$ 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 $-4/3e$ is produced instead of the SM top quark. The exotic scenario is found to be excluded at more than 5σ CL.

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