Письма в ЭЧАЯ. 2007. Т. 4, № 6(142). С. 821–830

MEASUREMENT OF THE TOP QUARK CHARGE AT THE ATLAS DETECTOR

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We have investigated the possibility of reconstructing the top quark charge through measurement of its decay product charges at the ATLAS detector. Verification of the hypothesis about alternative interpretation of top-quark experimental data has been considered as well. The method of «semileptonic B-meson decay» was applied for reconstructing the b-jet charge. A statistical significance of more than 5σ can be achieved using this method after analyzing 1 fb^{-1} of $t\bar{t}$-pairs data. The analysis was carried out with HERWIG and PYTHIA generators and using the GEANT4 detector simulation package.

Исследована возможность восстановления заряда топ-кварка посредством измерения зарядов продуктов его распада на установке АТЛАС. Также рассмотрена гипотеза об альтернативной интерпретации экспериментальных данных. Для восстановления заряда b-струи применен метод «полулептонного распада B-мезона». Использование этого метода позволяет достичь статистической значимости более 5σ после анализа 1 фб$^{-1}$ данных с $t\bar{t}$-событиями. Анализ проводился с использованием генераторов событий HERWIG и PYTHIA и пакета моделирования экспериментальной установки GEANT4.

PACS: 14.65.Ha

INTRODUCTION

The Large Hadron Collider (LHC) is expected to start in summer 2007 at CERN. It will be accelerator of the protons to the energy $\sqrt{S} = 14$ TeV at luminosities (1–2) $\cdot 10^{33}$ cm$^{-2} \cdot$ s^{-1} at the beginning of operation (low luminosity) and 10^{34} cm$^{-2} \cdot$ s^{-1} three years later (high luminosity). The top quark physics is one of the main objectives of the LHC [1].

There are many reasons to study the top quark properties. The top quark is the heaviest known elementary particle, its mass was measured to be $M_{\rm top} = (172.7 \pm 2.9)$ GeV/c^2 (combination of CDF and D$\emptyset$ results at the Tevatron) [2]. Because of its short lifetime ($\tau \sim 10^{-25}$ s, $\Gamma_t \gg \Lambda_{\rm QCD}$) it is the only quark that does not hadronize. Investigation of the top quark could help to understand the mechanism of electroweak symmetry breaking, since its mass is very close to the vacuum expectation value of the Higgs field. The most favoured framework to describe electroweak symmetry breaking is the Higgs mechanism. The masses of W and Higgs bosons depend on the top quark mass through radiative corrections (via the so-called Δr parameter).

The major process for $t\bar{t}$-pair production at the LHC is the gluon–gluon fusion, its branching ratio is about 87%, quark–antiquark annihilation processes are responsible for remaining 13%. The cross section of $t\bar{t}$-pair production at the LHC energies is predicted to be

$\sigma_{t\bar{t}} \approx 833$ pb and it is expected about 8 million $t\bar{t}$ pairs per year. At the same time, these $t\bar{t}$ events will manifest as a significant background for many search channels (for example, for SUSY). The CKM matrix element $|V_{tb}| \approx 1$, therefore, the branching ratio of the top quark decay to W boson and b quark is $B(t \to bW) \approx 1$. Thus, there are three signatures of $t\bar{t}$-pairs decay, which are characterized through the decay of the W boson (leptonically $W \to l\nu$ or hadronically $W \to q_i\bar{q}_j$). About 5% of all $t\bar{t}$-pairs decay through «dilepton channel» (both W bosons decay through $W \to l\nu$), «single lepton plus jets» decay mode takes about 30% (one W decays leptonically and the other W decays hadronically) and almost 65% of all $t\bar{t}$ pairs fall into «multi-jet» sample (both of W bosons decay to quark–antiquark pair or at least one W decays via $W \to \tau\nu_\tau$). Only electrons and muons are considered as leptons here [3].

The Standard Model unambiguously predicts that the top quark charge equals to $+2e/3$. It was not possible since last time to measure the top quark charge at the CDF and D$\emptyset$ collaborations, because of insufficient statistics, that did not allow one to analyze correlations of b quarks and W bosons from decay of $t\bar{t}$ pairs. But recent preliminary results concerning the top quark charge at the D$\emptyset$ experiment at the Tevatron show that $Q_{\rm top} = +2e/3$ at 94% C.L. using the weighting method of b-jet charge determination [4]. But, the results of the last precise electroweak measurements at the LEP and SLC demonstrate that the top quark mass may be more than 230 GeV (from decay $Z \to b\bar{b}$) [5].

Measuring of the top quark charge is one of the tasks of the top physics to be studied at the ATLAS experiment. There are several ways to measure the top quark charge [6, 7]. One of them is based on direct measurement of the top-quark electromagnetic coupling through photon radiation in $t\bar{t}$ events, the second method is based on the reconstruction of the charges of the top-quark decay products [8]. In this case one needs to explore the correlations between the b quarks and W bosons.

1. TOP–ANTITOP PAIR DECAY MODES AND KINEMATIC SELECTION CRITERIA

Main decay channel of the top quark is to the b quark and W^+ boson ($t^{+2/3} \to W^{+1}b^{-1/3}$). Thus, one has four particles after top–antitop pair decay: b quark, $\bar{b}$ quark, W^+ boson and W^- boson. Then b quark and $\bar{b}$ quark produce hadronic jets (b-jets), each of W bosons decays either to two leptons ($e\nu_e$, $\mu\nu_\mu$ or $\tau\nu_\tau$) or to light quark–antiquark pair, which in their turn hadronize.

The final state topology of $t\bar{t}$ events then can be divided into three groups [9]:

- *multi-jet sample:* 65.5% of all $t\bar{t}$ events, where both of W bosons decay to quark–antiquark pair ($t\bar{t} \to WWb\bar{b} \to (jj)(jj)(b\bar{b})$). However, these events suffer from a very large background from QCD multi-jet events;
- *dilepton sample:* 4.9% of all $t\bar{t}$ events, where each W decays leptonically ($t\bar{t} \to WWb\bar{b} \to (l\nu)(l\nu)(b\bar{b})$). Background processes for these events are Drell–Yan processes, processes with Z boson + jets, two W bosons + jets and $b\bar{b}$-pair production;
- *single lepton plus jets sample:* 29.6% of all $t\bar{t}$ events, where one W decays leptonically and the other W decays hadronically ($t\bar{t} \to WWb\bar{b} \to (l\nu)(jj)(b\bar{b})$). Background processes for them are W boson + jets, Z boson + jets, Z-bosons pairs, W-bosons pairs, W-boson + Z-boson production.

In this work we analyze single lepton plus jets events (Fig. 1), because selection criteria [3] for this channel give the best signal-to-background ratio.

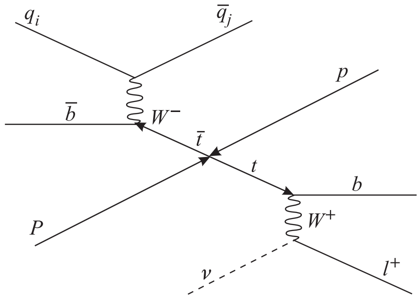

Fig. 1. Diagram of the single lepton plus jets channel in the $t\bar{t}$ production

1.1. Selection of Single Lepton Plus Jets Events. Single lepton plus jets events are characterized by the presence of one isolated charged lepton with large transverse momentum, large transverse momentum loss (carried away by neutrino) and presence of four or more hadron jets, two of which are b-jets. The presence of a high p_T isolated electron or muon allows these events to be triggered efficiently.

Nevertheless, the main background processes for this type of events, which have similar signature, are:

$$\begin{aligned}&W + \text{jets} \to l\nu + \text{jets},\\&Z + \text{jets} \to ll + \text{jets},\\&W + W \to l\nu + \text{jets},\\&W + Z \to l\nu + \text{jets},\\&Z + Z \to ll + \text{jets},\\&W + b\bar{b} \to ll + \text{jets}.\end{aligned}$$

Comparison of cross sections of these background processes with cross section of the process $t\bar{t} \to WWb\bar{b} \to (l\nu)(jj)(b\bar{b})$ without applying any kinematic selection criteria, gives ratio of signal to background $\approx 10^{-5}$. The following kinematic cuts have been applied to suppress such a high background [10]. We require:

• the presence of one charged isolated lepton with transverse momentum $p_T > 20$ GeV in pseudorapidity region $|\eta| < 2.5$ (to single out W from the top or antitop quark decay);

• total transverse momentum loss $p_t^{\text{miss}} > 20$ GeV (due to the neutrino);

• presence of at least four hadronic jets with transverse momentum $p_T > 40$ GeV in pseudorapidity region $|\eta| < 2.5$, two of which are b-jets.

Applying of these selection criteria gives signal-to-background ratio S/B ≈ 30, but at the same time, only 2.7% of all lepton plus jets events pass these criteria. As a result, one expects $\sim 64\,000$ single lepton plus jets events and around 2000 background events per year at the LHC at low luminosity [15].

1.2. Invariant Mass of the System «Lepton + b-Jet». To reconstruct the top quark charge, it is necessary to associate the b-jet and the single isolated charged lepton originated from the same top quark. Let us mark the combination of isolated charged lepton and b-jet coming from the same top quark decay, as a «true combination», and the case of isolated charged lepton and b-jet coming from different top quarks, as a «false combination».

The criterion for invariant mass of the «lepton + b-jet» system m_{lb} has been applied to reconstruct the «true combination». This criterion is based on the fact that the invariant mass of «true combination» of the «lepton + b-jet» system is always less or equal to the top quark mass, due to some missing energy carried away by neutrino:

$$m^2_{t\to Wb} = m^2_{Wb} = [(E_l + E_b) + E_\nu]^2 - [(\mathbf{p}_l + \mathbf{p}_b) + \mathbf{p}_\nu]^2 =$$
$$= \left[(E_l + E_b)^2 - (\mathbf{p}_l + \mathbf{p}_b)^2\right] + 2\left[(E_l + E_b)\cdot E_\nu - (\mathbf{p}_l + \mathbf{p}_b)\cdot \mathbf{p}_\nu\right] \geqslant m^2_{lb}.$$

Since in case of the «false combination» isolated charged lepton and b-jet do not correlate, invariant mass of the «lepton + b-jet» system may be either less or more than the top quark mass, in contrast to the «true combination».

Assuming all mentioned above, it is possible to choose selection criterion allowing one to reject «false combinations» of the isolated charged lepton and b-jet. It is described in detail in Subsec. 3.1.

2. METHODS OF THE b-JET ELECTRIC CHARGE RECONSTRUCTION

While the electric charge of W boson can be determined through its leptonic decay (due to the charge conservation), determination of the b-quark charge is rather a difficult task. There are at least two methods:

• *The weighting method* [11] relies on weighted sum of charges of all hadrons belonging to the given b-jet:

$$Q_{b\text{-jet}} = \frac{\sum\limits_i^N q_i \left|\mathbf{j}\cdot\mathbf{p}_i\right|^k}{\sum\limits_i^N \left|\mathbf{j}\cdot\mathbf{p}_i\right|^k},$$

where N is the number of charged particles inside the b-jet; q_i and p_i are charge and momentum of the ith particle; $\mathbf{j}$ is b-jet axis; k is some auxiliary exponent factor. This method was applied at the $D\emptyset$ experiment to determine the b-jet charge in 17 «single lepton plus jets» events. The tracks must have $\triangle R \leqslant 0.5$, $p_T > 0.5$ GeV and be within 0.1 cm of the primary vertex in the z direction (along the beam axis). The chosen value of exponent ($k = 0.6$) and $\triangle R$ (jet cone size in the (η, ϕ) space) are the result of an optimization using fully simulated Monte Carlo $t\bar{t}$ events [4].

• *The semileptonic B-meson decay method* is based on the reconstruction of the b-jet charge via determination of the soft lepton charge (resultant of the B-meson decay), which presents inside the jet:

$$b \to c, u + l^- + \bar{\nu}, \quad \bar{b} \to \bar{c}, \bar{u} + l^+ + \nu.$$

In the present work this very method for the reconstruction of the b-jet charge has been used.

3. SIMULATION AND ANALYSIS

For the analysis we used two kinds of samples. The main is the so-called «Rome T1 sample», where 1 million $t\bar{t}$ events generated by MC@NLO HERWIG [12] Monte Carlo generator are forced so that either the top or antitop decays to $b + \nu + l$ with l being e, μ or τ. This means that «Rome T1 sample» contains only lepton + jets and dilepton events. The sample was produced with the ATLAS detector full simulation done by GEANT4. This is the main sample for our analysis. The second type of samples is fast simulated samples, where the simulation has been done by ATLFAST [13]. We have two such kinds of samples, both contain 1 million $t\bar{t}$ events, but one of them was produced with generator HERWIG and the second one with PYTHIA [14]. We used these samples for comparison between full and fast simulations and for simulation of «exotic» quark scenario (see Subsec. 3.3).

«Rome T1 sample» was generated, simulated and digitized in ATHENA framework release 9.0.4, the reconstruction has been done with ATHENA 10.0.2. For fast simulation we used ATHENA 11.0.2. Cone algorithm for jet reconstruction was used with cone size $\triangle R = \sqrt{\triangle\phi^2 + \triangle\eta^2} = 0.4$. We employed CTEQ5M and CTEQ5L parton distribution functions for fast and full simulations, respectively. As the Standard Model input parameters we used the default parameters of HERWIG and PYTHIA in ATHENA releases 9.0.4 and 11.0.2 for full and fast simulations, respectively.

Table 1. **Kinematic criteria and their influence on $t\bar{t}$-events sample**

Selection criteria	Number of events		
	Rome T1	ATLFAST	
Sample / Generator	HERWIG	HERWIG	PYTHIA
All generated $t\bar{t}$ events	1.000.000	1.000.000	1.000.000
Expected number of the «single lepton plus jets» events	$\sim$ 300.000	$\sim$ 300.000	$\sim$ 300.000
1 isolated charged lepton with $p_T > 20$ GeV and $\|\eta\| < 2.5$	143.271	265.924	233.604
1 isolated charged lepton with $p_T > 20$ GeV, $\|\eta\| < 2.5$, $p_T^{\text{miss}} > 20$ GeV	130.306	240.199	211.272
1 isolated charged lepton with $p_T > 20$ GeV, $\|\eta\| < 2.5$, $p_T^{\text{miss}} > 20$ GeV, at least 4 jets with $p_T > 40$ GeV, $\|\eta\| < 2.5$	24.764	58.573	73.489
1 isolated charged lepton with $p_T > 20$ GeV, $\|\eta\| < 2.5$, $p_T^{\text{miss}} > 20$ GeV, at least 4 jets with $p_T > 40$ GeV, $\|\eta\| < 2.5$, 2 of which are b-jets	8.420	11.556	13.537

As was mentioned above, only about 30% of all $t\bar{t}$ events are the «single lepton plus jets» events. Applying kinematic selection criteria described in Subsec. 1.1 step by step, one can see from Table 1 how they influence $t\bar{t}$-events sample.

3.1. Invariant Mass Criteria. First of all, for reconstruction of the top-quark electric charge it is necessary to determine correlations between isolated charged lepton and b-jet, to be sure the charged isolated lepton and the b-jet both originate from the same top quark candidate.

For this purpose 100.000 $t\bar{t}$ events have been analyzed at the generator level (PYTHIA generator, generation without any kinematic criteria). This level gives opportunity to track the topology of every event and, in particular, to distinguish between «true» and «false» combinations of lepton and b-jet.

Figure 2 presents invariant mass distribution of isolated charged lepton and b quark (m_{lb}). One can see that invariant masses of almost all «true combinations» are less than 160 GeV. Therefore, we can introduce $m_{\text{cut}} = 160$ GeV. As was expected, «false combinations» have the invariant mass values both less and larger than top quark mass.

Since invariant masses of «true combinations» are mainly less than m_{cut} and the invariant masses of the «false combinations» are both less and more than m_{cut}, it is possible to choose «true combination» by the following methods:

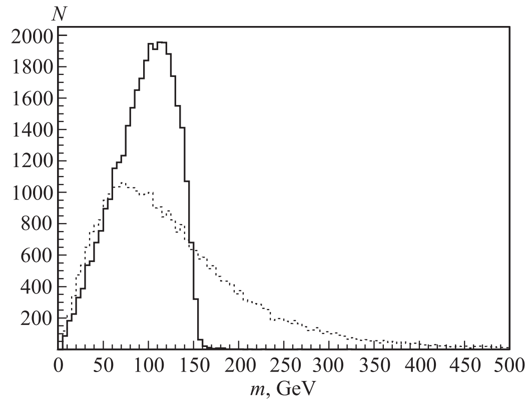

Fig. 2. Distribution of «true combination» (solid line) and «false combination» (dashed line). One can see that invariant masses of almost all «true combinations» have invariant masses $m_{lb} < m_{\rm cut} =$ 160 GeV

a) $m_{lb_1} \leqslant m_{\rm cut}$ and $m_{lb_2} > m_{\rm cut}$, then lb_1 is «true combination»,
b) $m_{lb_1} > m_{\rm cut}$ and $m_{lb_2} \leqslant m_{\rm cut}$, then lb_2 is «true combination»,
c) $m_{lb_1} \leqslant m_{\rm cut}$ and $m_{lb_2} \leqslant m_{\rm cut}$, then event is rejected,
d) $m_{lb_1} > m_{\rm cut}$ and $m_{lb_2} > m_{\rm cut}$, then event is rejected.

Here lb_1 is the combination of isolated lepton and one of two b-jets, lb_2 is the combination of lepton and the other b-jet.

3.2. Determination of the Initiator of b-Jet. After definition of the «true» combination the next step is to determine the charge of the initiator of the b-jet. It can be positive or negative depending on whether b quark or $\bar{b}$ quark produces that jet. As was noted above, the «semileptonic B-meson decay» method of reconstruction of b-jet charge has been used. The negative charged lepton comes from decay of B meson containing b quark ($b^{-1/3} \to c, u + l^- + \bar{\nu}$), and the positive charged lepton comes from decay of B meson containing $\bar{b}$ quark ($\bar{b}^{+1/3} \to \bar{c}, \bar{u} + l^+ + \nu$). Therefore, the charge of non-isolated lepton inside b-jet could indicate the initiator of b-jet. Nevertheless, there could be positive charged leptons inside b-jet, initiated by b quark. The first reason is the oscillations of B^0 mesons to $\bar{B}^0$ mesons. The second reason is the semileptonic decay of D mesons inside b-jets, from which mainly comes opposite charged lepton to the leptons from B mesons. We used only muons as leptons here. Muon was accepted as a charged non-isolated lepton if it is located inside $\triangle R < 0.4$ cone in (η, ϕ) space around the b-jet axis, where η is pseudorapidity and ϕ is the azimuthal angle.

It means that it is not possible to determine unambiguously the initiator of the b-jet, nevertheless, there is a possibility to find contribution of negative and positive charged leptons in jets, produced by b quarks.

The isolated charged lepton from top quark decay has the same sign of charge as the top quark charge and opposite to the b-quark charge. Thus, if reconstructed invariant mass of positive charged isolated lepton and b-jet forms «true combination» (originated from the same top quark), it means that the initiator of this b-jet is b quark:

$$t^{+2/3} \to W^{+1} b^{-1/3} \to l^+ \nu b^{-1/3}.$$

Similarly, the «true combination» of the negative charged isolated lepton and b-jet means that the initiator is $\bar{b}$ quark:

$$t^{-2/3} \to W^{-1}\bar{b}^{+1/3} \to l^{-}\bar{\nu}\bar{b}^{+1/3}.$$

The further analysis is done using only full simulated samples. Table 2, Fig. 3 (a, b) and Fig. 4 (a, b) show the contributions of both signs charged non-isolated leptons inside b-jets after analyzing of $\sim$ 300.000 fully simulated single lepton + jets events. The only cut for non-isolated lepton is $p_T > 10$ GeV. Though there are many positive charged leptons inside b-jets, produced by b quarks, the number of negative charged leptons is typically higher.

Table 2. **Number of b-jets with charged non-isolated lepton inside ($t\bar{t}$ events)**

Cut for non-isolated lepton	With *positive* charged isolated lepton		With *negative* charged isolated lepton	
	$N(l^-)$	$N(l^+)$	$N(l^-)$	$N(l^+)$
$p_T > 10$ GeV	145	107	70	109
$p_T > 25$ GeV	67	35	21	45

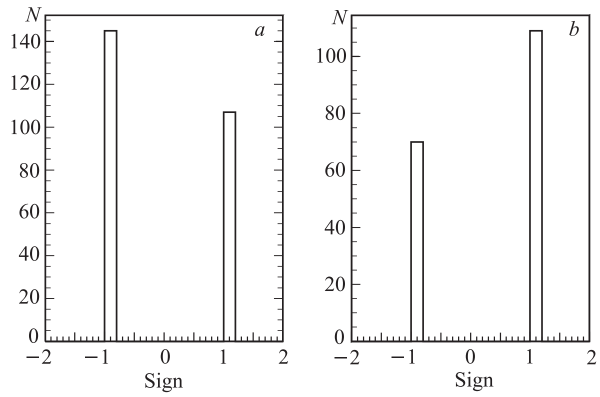

Fig. 3. The $t\bar{t}$ events: contributions of both sign charged non-isolated leptons with $p_T > 10$ GeV inside b-jets: a) associated with positive charged isolated leptons; b) associated with negative charged isolated leptons

Let us introduce the ratio

$$\varepsilon_b = \frac{N(l^+) - N(l^-)}{N(l^+) + N(l^-)},$$

where $N(l^-)$ is the number of b-jets with negative charged lepton inside, and $N(l^+)$ is the number of b-jets with positive charged lepton inside.

The value of ε_b is the mean value of non-isolated muons charges in all events and shows the excess of positively charged leptons over negative ones for b-jets. From Table 2 the following values of ε_b, $\varepsilon_{\bar{b}}$ and corresponding statistical errors have been obtained:

$$\varepsilon_b = \frac{107 - 145}{107 + 145} = -0.15 \pm 0.05, \qquad \varepsilon_{\bar{b}} = \frac{109 - 70}{109 + 70} = 0.22 \pm 0.06.$$

We also have performed the same procedure using cut on non-isolated lepton $p_T > 5, 15, 20, 25$ GeV (Fig. 5). Increasing the value of cut we want to decrease the number of b-jets with non-isolated leptons coming from D-mesons decay. These leptons

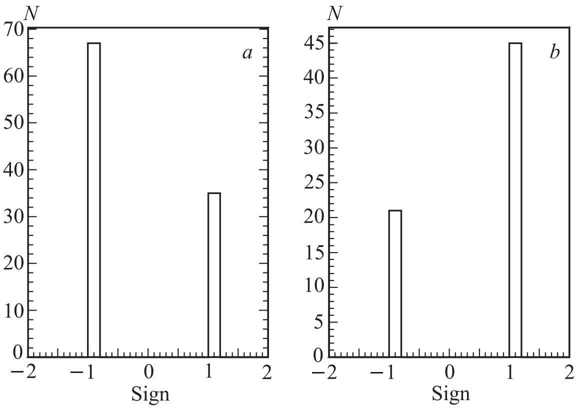

Fig. 4. The $t\bar{t}$ events: contributions of both sign charged non-isolated leptons with $p_T > 25$ GeV inside b-jets: a) associated with positive charged isolated leptons; b) associated with negative charged isolated leptons

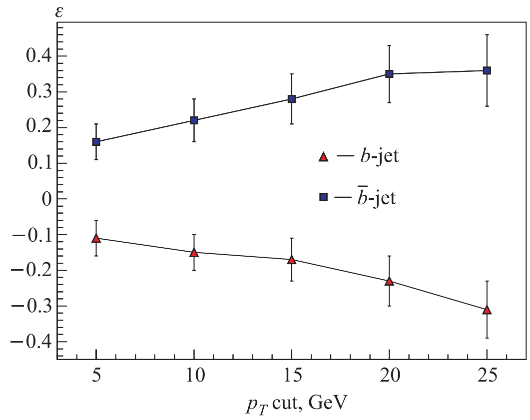

Fig. 5. Dependence of ε on cut on the p_T of non-isolated muon

have smaller energy than leptons from B-mesons decay. From Fig. 4, a and Table 2 one can see that the number of all b-jets decreases, but the number of b-jets which are initiated by b quark and have positive charged lepton inside decreases more distinctly than the number of b-jets with negative charged lepton inside. For example, the corresponding values of ε with cut on non-isolated lepton $p_T > 25$ GeV are

$$\varepsilon_b = -0.31 \pm 0.08, \qquad \varepsilon_{\bar{b}} = 0.36 \pm 0.10.$$

3.3. Exotic Heavy Quark. One of the purposes of this work was also to consider the hypothesis about alternative interpretation of the experimental top quark data in terms of a heavy top-like quark with $Q \neq +2e/3$. Here, the supposed difference between the SM top quark and the exotic heavy quark is just the value of charge, $Q_{\rm exotic} = -4e/3$. Main decay mode of this exotic heavy quark differs from the top-quark decay mode by the sign of the W-boson charge:

$$t^{+2/3} \to b^{-1/3} + W^{+1}, \qquad Q^{-4/3}_{\rm exotic} \to b^{-1/3} + W^{-1},$$
$$\bar{t}^{-2/3} \to \bar{b}^{+1/3} + W^{-1}, \qquad \bar{Q}^{+4/3}_{\rm exotic} \to \bar{b}^{+1/3} + W^{+1}.$$

One can see that in case of exotic quark positively charged isolated lepton from W^+ decay will be associated with b-jet produced by $\bar{b}$ quark. This means that if we take the positively charged isolated leptons and calculate ε for the b-jets associated with these leptons we will get the value of ε for $\bar{b}$ quark (ε value is positive). Using this we are going to distinguish between top and exotic quarks, because in case of top quark the b-jet associated with positively charged isolated lepton has the signature of b quark (ε value is negative). So, for the observation of the difference between top and exotic quarks one has just to distinguish between b-jets produced by b quarks and b-jets produced by $\bar{b}$-quark. This was done in Subsec. 3.2 and, as one can see from Fig. 5, they are distinguishable.

CONCLUSION

We have studied possibility of the top-quark charge reconstruction via measurement of its decay product charges at the ATLAS detector. In its turn, b-jet charge has been reconstructed using information of non-isolated lepton's charge inside that b-jet. This method differs from the method which is used in the D∅ experiment. Variable ε has been introduced to verify the hypothesis about «exotic» quark. Though value of ε depends on generator type (hadronization, shower type, etc.), it is always negative for the $t\bar{t}$ events and is always positive for $Q_{\rm exotic}\bar{Q}_{\rm exotic}$ events. This means that top quark and «exotic» quark can be distinguished by the sign of ε. Applying cut on p_T of non-isolated lepton let us increase the difference of ε values for top and «exotic» quarks and we need less number of events for 5σ separation of $\varepsilon^{\rm top}$ and $\varepsilon^{\rm exotic}$. This cut has to be optimized, but at first sight it is seen that analyzing 300.000 lepton + jets events one can achieve more than 5σ separation.

The main outlook is that top quark charge can be verified using data from the ATLAS detector after some days operation, and perhaps the charge will be one of the first parameters of top quark measured with ATLAS.

We believe the systematics and background have to be further investigated.

Acknowledgements. We are grateful to S. Tokar and B. Zilka for fruitful cooperation and to D. Froidevaux for useful advice. We are also very grateful to many other colleagues who are taking part in the ATLAS experimental and software development.

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Received on October 23, 2006.