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Autoreferát dizertačnej práce

Measurement of the top quark electric charge at LHC in the ATLAS experiment

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Contents

1 Introduction

In this note, a measurement of the top quark charge at the Large Hadron Collider with 2.05 fb^{-1} of proton-proton collision data collected by the ATLAS experiment at $\sqrt{s} =$ 7 TeV is presented. The top quark charge measurement is based on reconstructing the charges of the top quark decay products. The dominant decay channel of the top quark, $t \rightarrow W^+b(\bar{t} \rightarrow W^-\bar{b})$, 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.

One of the reason why it is needed to study this top quark quantity is that it can confirm that the quark observed since 1995 at Tevatron is really the top quark of the Standard model. It is generally accepted that the particle discovered at Fermilab in 1995 [12, 11] is the Standard model top quark. However, from the analysis carried out by the CDF and D0 collaborations, the possibility that the top quark charge is different from the Standard Model value is not completely ruled out, though both the experiments lately reported a preference for the SM scenario [10, 5]. An impetus for the top quark charge study was the theoretical model assuming existence of an "exotic“ (XM) quark of charge -4/3 and mass $\approx$ 170 GeV [4]. The exotic scenario assumes existence of additional heavy quarks Q_3 and Q_4 with charges -1/3 and -4/3, respectively. With the additional heavy quarks two physical quark doublets, $(Q_3, Q_4)_\mathrm{L}$ and $(Q_3 \cos\theta_3 - \mathrm{b} \sin\theta_3, Q_4)_\mathrm{R}$, and one singlet $(Q_{3\mathrm{R}} \sin\theta_3 + \mathrm{b_R} \cos\theta_3)$ are added to the SM quark doublets and singlets. Hence, in addition to the SM, Q_3 mixes with b (mixing angle θ_3) and Q_4 decays into $b + W^-$. In this scenario, which correctly describes the electroweak data, the top quark has mass around 270 GeV while the mass of Q_4 quark should be around 170 GeV.

2 The goals of the thesis

The goal of my thesis is to reconstruct the top quark electric charge at the ATLAS experiment.. My ultimate goal is to distinguish between the Standard model and exotic model scenarios.

With these goals in sight I will mainly concetrate on the following partial tasks:

- to improve the b-jet charge algorithm. I want to tune a subset of parameters to maximize the efficiency of analysis (number of tracks, b-tagging, the maximal size of the cone between a b-jet and track belonging to this b-jet, critical mass, threshold in the ivariant mass criterium)
- background studies
- to determine the systematic uncertainties

3 Top quark production at the LHC

Top quarks can be produced either through the strong interaction as top quark and anti-top quark pairs ($t\bar{t}$) or through the electroweak interaction called single top quark production. The cross-sections of single top processes are approximately an order smaller than that for the $t\bar{t}$ production. The LHC is designed to produce millions of $t\bar{t}$ pairs per year ($\sim 10fb^{-1}$).

4 Event selection

At the reconstruction level (for both the simulated and data samples) we reconstruct only the lepton+jets events. In compliance with this, the standard ATLAS lepton+jets criteria have been applied in the present top quark charge analysis.

For the selection of candidate events the single leptonic trigger was required. In the case of data, for the electron runs the single lepton triggers EF_e20_medium (the periods B2-G5, I and J) and EF_e22_medium (period K) were required. In the case of muon runs for all periods the trigger EF_mu18 was required. In the Monte Carlo case also the following single lepton triggers were required: EF_e20_medium and EF_e22_medium (electrons) and EF_mu18 (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-$\mathrm{k_t}$" 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 JetFitterCombNN with a weight exceeding 0.35.

This common selection was followed by requirements two additional cuts for our analysis: at least 2 good jets with JetFitterCombNN weight > 0.35 and fulfilling pairing condition (see Eq. 3).

5 Methods of top quark charge determination

In a nutshell, the essence of the top quark charge determination is in the following:

- The charge of the W boson coming from the top quark (exotic quark) decay should be determined. It is easy to do using its leptonic decay (the sign of the W boson and its decay lepton is the same).

- The average b-jet charge determined through b-jet tracks charges should be negative in the case if the b-jet is initiated by a b-quark and should be positive if it is initiated by a $\bar{b}$-quark.
- Selection criteria for pairing of lepton and b-jet originating in the same top quark must be found. The jet initiated by b-quark should be associated with ℓ^+ (ℓ^-) for the Standard model (exotic) case, in order to reconstruct the top quark charge.

In this analysis we restricted ourselves to the $t\bar{t}$ lepton+jets events.

5.1 Weighting procedure for b-jet charge calculation

For the determination of the effective b-jet charge we have employed a weighting technique [15, 8] in which the b-jet charge is defined as a weighted sum of the b-jet track charges:

$$q_{\rm bjet} = \frac{\sum_{\rm i} q_{\rm i} |\vec{j} \cdot \vec{p}_{\rm i}|^{\kappa}}{\sum_i |\vec{j} \cdot \vec{p}_{\rm i}|^{\kappa}} \tag{1}$$

where $q_{\rm i}(p_{\rm i})$ is the charge (momentum) of the $i^{\rm th}$ track , the $\vec{j}$ defines the b-jet axis direction and κ is a parameter which was optimised (for the best separation of b- and $\bar{b}$-jets) to 0.5.

The variable which is used to distinguish between the Standard model and exotic model scenarios is the combined lepton - b-jet charge (further only the combined charge) which is defined according to:

$$Q_{\rm comb} = Q^{\ell}_{b-\rm jet} \cdot Q_{\ell}, \tag{2}$$

where $Q^{\ell}_{\rm bjet}$ and Q_{ℓ} are the b-jet charge calculated by Eq.1 and the lepton charge, respectively, where the b-jet and lepton ℓ come from the same top quark. The charge weighting procedure was optimised also for the minimal track $p_{\rm T}$, maximal number of tracks used for the b-jet charge calculation and the size of cone in frame of which track pointing to a b-jet are included for the charge calculation. For the optimisation we have used the standard MC@NLO $t\bar{t}$ sample. As a result of the optimisation in the weighting procedure is used: as a maximum 10 tracks pointing to b-jet within the cone ΔR <0.25 and only tracks with $p_{\rm T} > 1$ GeV are taken.

5.2 Lepton and b-jet pairing algorithm

The lepton and b-jet pairing was done using the invariant mass distribution of the lepton and the b-tagged jet, $m(\ell, b_{\rm jet})$. If the assignment is correct, $m(\ell, b_{\rm jet})$ cannot exceed the top quark mass, otherwise there is no such restriction, as can been seen in Figure 1, where the signal sample with the standard cuts applied was analysed.

We require double b-tagged events (see Sec.4). Only those events with b-jets that satisfy the conditions

$$m(\ell, b^{(1,2)}_{\rm jet}) < m_{\rm cr} \quad \text{and} \quad m(\ell, b^{(2,1)}_{\rm jet}) > m_{\rm cr} \tag{3}$$

have been accepted. The optimal value for the pairing mass cut, $m_{\rm cr}$, is a trade-off between the efficiency (ϵ) and purity (P) of the pairing method. The factor $\epsilon(2P-1)^2$

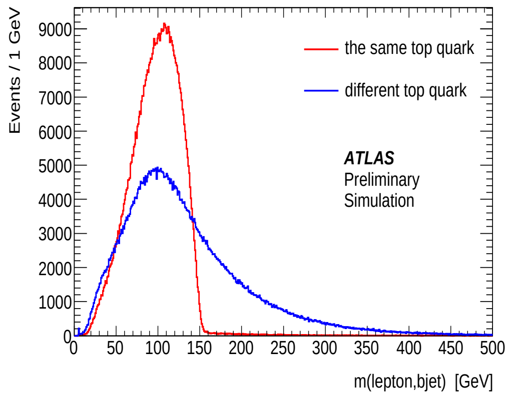

Figure 1: Lepton - b-jet invariant mass spectra for the lepton and b-jet pairs from the same top quark (red line) and for those with origin in different top quarks (blue line).

was maximised to find the optimum value of $m_{\rm cr}$. The maximum of the optimisation factor was found in the region from 140 GeV to 165 GeV, where the factor was nearly constant. The optimal value for the pairing mass cut was taken to be $m_{\rm cr} = 155$ GeV.

6 Data samples

6.1 Monte Carlo samples

The Monte Carlo (MC) samples used for the top quark charge analysis were produced by the full GEANT4-based ATLAS detector simulation and reconstruction code. The $t\bar{t}$ signal has been produced using the MC@NLO generator [9] for the parton level hard part of $t\bar{t}$ production and using the HERWIG generator [6] and JIMMY [13] for simulation of the hadronisation and fragmentation processes (in the ATLAS coding - sample 105200) and the POWHEG generator (parton level) in combination with the generator PYTHIA (sample 105861) and HERWIG (sample 105860) used for hadronisation. All the samples have been weighted using K-factors to the NLO cross-sections. The $t\bar{t}$ samples generated using the LO ACERMC generator [14] interfaced with PYTHIA [16] (sample 105205) for the hadronisation and fragmentation, were used. Also samples for the assignment of the uncertainty due to ISR/FSR[1] have been generated with ACERMC (ME, LO) with PYTHIA. For the study of top quark mass systematic uncertainties have been generated $t\bar{t}$ samples with different values of top quark mass using MC@NLO generator with Herwig. MC@NLO samples are generated with 0.111 $W\to \ell\nu$ branching ratio (one flavor) while POWHEG samples are generated with 0.108. For setting the K-factors the reference $W \to \ell\nu$ ratio of 0.108 (per flavour) is used (in agreement with the PDG2010 value).

The background processes were also simulated using the ATLAS detector simulation and reconstruction code. For the single top quark signal production, the MC@NLO in combination with HERWIG/JIMMY was used. The ALPGEN [7] was interfaced to HERWIG/JIMMY to produce W+jets and Z+jets samples. The di-boson sample have been generated using HERWIG at leading order, and the corresponding production

[1]ISR/FSR means Initial and Final State Radiation

cross-sections were normalised to the next-to-next-to leading order predictions using k-factors.

6.2 Collision data

The measurement presented here is based on proton-proton collision data collected at a centre-of-mass energy $\sqrt{s} = 7$ TeVwith the ATLAS detector at the LHC. A bunch spacing of 50 ns was used. The accumulated data (periods B - K) corresponding to an integrated luminosity of 2.05 ± 0.08 fb^{-1} have been used, after the preselection of the delivered raw data using the corresponding GoodRunsList (GRL) [1].

7 Signal estimation

In this section, assuming the Standard model scenario of top quark production and decay, the ATLAS experiment potential for the determination of the top quark charge at 7 TeV centrum mass energy has been investigated using Monte Carlo samples. On parton level the lepton+jets ($t\bar{t} \rightarrow l\nu jjb\bar{b}$) and dilepton ($t\bar{t} \rightarrow l\nu l\nu b\bar{b}$) branches of the $t\bar{t}$ production have been used. On reconstruction level only the lepton+jets (LJ) events are taken into account. For the simplicity of analysis the results concerning the combined charge, $Q_{\rm comb}$, i.e. the variable which is used to distinguish between the SM and XM scenarios, are presented here mainly for the leptonic branch of $t\bar{t}$ events tough the analysis of the hadronic branch has been also carried out and for a comparison are sometimes also shown.

7.1 Reconstructed signal distribution

In the Monte Carlo analysis of the top quark charge the MC@NLO, POWHEG and ACERMC $t\bar{t}$ samples were used. As a default MC generator, MC@NLO was taken. The sizes of the MC@NLO, POWHEG and ACERMC samples were 15 millions and 1 million (POWHEG and ACERMC) events, respectively. The b-jet charge spectra reconstructed for the $t\bar{t}$ signal events, using MC@NLO, are presented in Figure 2 where the b-jet charge distributions for b-jets paired with positive (blue line) and negative (red line) leptons are shown after the invariant mass pairing. In addition, the $Q_{\rm comb}$ b-jet charge spectrum, defined as $Q(\ell) \times Q^{(\ell)}_{\rm bjet}$, has been reconstructed and depicted in the plot (black line).

From Figure 2, the shift of the mean b-jet charges associated with ℓ^+, $Q^{(+)}_{\rm bjet}$, and ℓ^-, $Q^{(-)}_{\rm bjet}$ is clearly seen.

In general, there is a good correspondence between the MC@NLO, POWHEG and ACERMC spectra. The combined (electon + muon branches) expectations are compatible at better than 4% level. A good agreement is also between the individual channels - the highest difference is between the electron branch and the muon branch results for POWHEG/PYTHIA generator (3σ difference).

To check the power of the lb pairing, we compare the results of b-jet charge reconstruction based on this pairing with that using MC matching. In the latter case the correspondence between parton level b-quark and reconstructed b-jet is required within

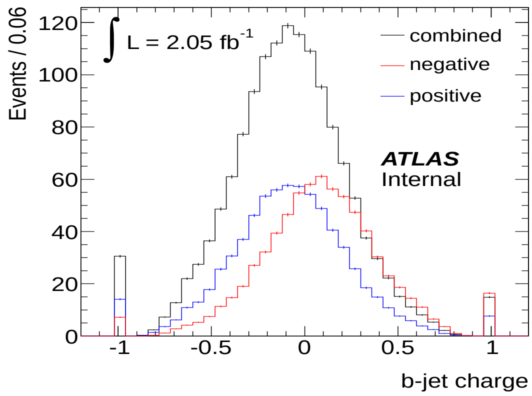

Figure 2: The b-jet charge associated with positive (blue line) and negative (red line) lepton and combined charge (black line); the invariant mass ℓb-pairing was used.

a cone of $\Delta R < 0.2$. The comparison was carried out using the MC@NLO $t\bar{t}$ samples and the results are shown in Table 1.

The higher magnitudes of the b-jet charges in the case of the MC matching can be explained by almost 100% purity of the pairing in this case. From Table 1 we see that the expected magnitudes of the combined charges for electrons and muons are compatible within statistical errors.

pairing	$Q^{(\mathrm{e})}_{\mathrm{comb}}$	$Q^{(\mu)}_{\mathrm{comb}}$	$< Q_{\mathrm{comb}} >$
MC matching	-0.1014 $\pm$ 0.0009	-0.1006 $\pm$ 0.0008	-0.1010 $\pm$ 0.0006
Invariant mass	-0.0800 $\pm$ 0.0008	-0.0780 $\pm$ 0.0007	-0.0790 $\pm$ 0.0005

Table 1: Comparison of the mean b-jet charges ($Q^{(\mathrm{e})}_{\mathrm{comb}}$, $Q^{(\mu)}_{\mathrm{comb}}$ and $< Q_{\mathrm{comb}} >$) for the $t\bar{t}$ MC@NLO signal obtained by the MC matching and invariant mass pairing.

An important issue at the combined b-jet charge reconstruction in the lepton+jet channel is what are the contributions of different topologies (lepton+jet and dilepton topology) to this reconstruction as well as what is the contribution of τ leptons. Therefore, we have investigated using Monte Carlo truth, the composition of the reconstructed events in comparison with that at the parton level.

The results, for the case when on the parton level we have lepton+jets and dilepton topologies and on the reconstructed level is there only lepton+jets topology. The reconstructed lepton+jets events consist from 86.7% lepton+jets events and in the 13.3% cases from the dilepton events at the parton level. For muons, the magnitude of $< Q_{\mathrm{comb}} >$ is slightly higher in the case of the dilepton events than in the lepton+jet case. In the electron channel the result is opposite, i.e. the magnitude of $< Q_{\mathrm{comb}} >$ is slightly lower in the case of dilepton events than in the lepton+jet case. In both cases the difference is not statistically significant.

The results of $< Q_{comb} >$ for the reconstructed lepton (e, μ) in $t\bar{t}$ sample with respect to the parton level leptons (e, μ or τ) in the lepton+jets events was studied. Only in the case when a muon at parton level was reconstructed as a electron is $Q_{comb} >$

0, but with very large uncertainty and tiny statistics. This result have negligible impact on the final results. Part of τ-leptons at parton level are reconstructed as electrons or muons. The combined charge of b-jets associated with individual leptons from these events are in a good agreement with each other, i.e. the type of lepton is well reconstructed.

		Muons		Electrons	
type gen	typ rec	N_{evnt}	$< Q_{\mathrm{comb}} >$	N_{evnt}	$< Q_{\mathrm{comb}} >$
LJ	LJ	1585.3	-0.0759± 0.0008	1202.9	-0.0809± 0.0009
DL	LJ	242.9	-0.0888± 0.0020	219.1	-0.0764± 0.0021

Table 2: The composition of the reconstructed $t\bar{t}$ MC@NLO sample with respect to the parton level composition – lepton+jets events (LJ), dilepton events (DL), number of events (N_{evnt}).

8 Background estimation

The main background processes for the top quark charge measurement in the lepton+jets channel are: W+jets production (the most significant background usually divided into W+heavy flavour (b-quarks only) jets (W+HF) and W+non-b parton jets (W+partons)), Z+jets, QCD multi-jets, di-boson and single top quark production. The single top production is not a genuine background as it gives the same sign of the b-jet charge asymmetry as the signal. The Monte Carlo simulation is expected to predict correctly all the processes with exception of the QCD multi-jets one. Though the probability of a multi-jet event to pass the event selection is very low, the production cross section for the multi-jet events is orders of magnitude above that of top quark pair production and due to fake leptons the multi-jet events can effectively contribute to background.

The QCD multi-jet background is determined with data driven techniques. The data driven methods are most appropriate to estimate the rate of fake leptons passing a given event selection. In our case we use the Matrix method [2], which is based on selecting two categories of events, using loose and tight lepton selection requirements. The number of events which contain the loose or tight leptons can be written as,

$$N^{\mathrm{loose}} = N_{\mathrm{r}}^{\mathrm{loose}} + N_{\mathrm{f}}^{\mathrm{loose}} \tag{4}$$

$$N^{\mathrm{tight}} = \epsilon_{\mathrm{r}} N_{\mathrm{r}}^{\mathrm{loose}} + \epsilon_{\mathrm{f}} N_{\mathrm{f}}^{\mathrm{loose}} \tag{5}$$

where $N_{\mathrm{r}}^{\mathrm{loose}}$ and $N_{\mathrm{f}}^{\mathrm{loose}}$ are the number of events containing real and fake leptons, respectively, which pass the loose lepton requirements and the quantities ϵ_{r} and ϵ_{f} are the efficiencies of the real and fake loose leptons to be selected also as the tight leptons. The efficiencies ϵ_{r} and ϵ_{f} are provided by means of the software package "FakeMakros". Using these efficiencies and Eq. 4 and 5, one can find the number of fake leptons which pass the tight lepton requirement, i.e. pass the $t\bar{t}$ selection requiring one tight lepton in event, $N_{\rm f}^{\rm tight}$ $(= \epsilon_{\rm f} \cdot N_{\rm f}^{\rm loose})$. This number can be expressed as follows:

$$N_{\rm f}^{\rm tight} = \frac{\epsilon_{\rm f}}{\epsilon_{\rm r} - \epsilon_{\rm f}} \left(\epsilon_{\rm r} N^{\rm loose} - N^{\rm tight}\right) \quad (6)$$

Note that having the number of events passing the loose and tight lepton selection and the efficiencies $\epsilon_{\rm r}$ and $\epsilon_{\rm f}$, we can estimate both the shape and number of multijet events passing the ℓ+ jets selection.

8.1 Background summary

The separate results for electron and muon branches after the all $t\bar{t}$ cuts (see Table **??**) used in the analysis including those used for the invariant mass pairing, are in Table 3. In the above mentioned table $N_{\rm lb}$ is the expected mean number of lepton–b-jet pairs (lb-pairs) and $< Q_{\rm comb} >$ is the mean b-jet charge (the mean combined charge) over the sample of selected events. At both quantities only the statistical errors are taken into account.

	electron		muon	
process	$N_{\rm lb}$	$< Q_{\rm comb} >$	$N_{\rm lb}$	$< Q_{\rm comb} >$
W+jets	77 ± 12	-0.077 ± 0.030	132 ± 18	-0.047 ± 0.032
Z+jets	9 ± 3	0.078 ± 0.153	15 ± 4	-0.179 ± 0.086
DiBoson	1 ± 1	-0.229 ± 0.573	2 ± 1	-0.071 ± 0.279
QCD (data driven)	18 ± 5	-0.018 ± 0.082	36 ± 7	-0.027 ± 0.038
nonT-bkgd	105 ± 13	-0.015 ± 0.041	183 ± 20	-0.052 ± 0.028
Single top	67 ± 11	-0.066 ± 0.042	80 ± 12	-0.051 ± 0.038
Signal	1422± 157	-0.080 ± 0.009	1828 ± 201	-0.078 ± 0.008
Signal + background	1594± 158	-0.075 ± 0.008	2094 ± 202	-0.074 ± 0.007

Table 3: The expected background after the invariant mass criterion separately for the electron and muon branch at the integrated luminosity 2.05 fb^{-1}, $N_{\rm lb}$ is the mean number of lepton–b-jet pairs, $< Q_{\rm comb} >$ is the reconstructed mean combined charge, All-bkgd (nonT-bkgd) is the full (without single top) background.

It should be noted that in the case of Table 3 only b-jets of leptonic branch are used for finding the mean combined charge ($< Q_{\rm comb} >$). The uncertainties in the expected number of the signal and background events include not only the statistical uncertainties but also the cross section uncertainties, which are at a level of 10% (signal, single top) up to 100% for QCD background, and uncertainties in the integrated luminosity (3.9%).

The background studies for this analysis require Monte Carlo samples of high statistics (in addition to the standard cuts the invariant mass criterion is highly restrictive) which are not always available with sufficient statistics. Nonetheless, as can be seen from Table 3, the non-top quark background is symmetric, i.e. the reconstructed mean combined charge, $< Q_{\rm comb} >$, is within errors compatible with 0. On the other hand, the single top background is correlated with the signal, i.e. it exhibits a similar b-jet charge asymmetry as that of the signal.

9 Results

In this section the experimental data collected by the ATLAS experiment are analysed. The integrated luminosity of the analysed sample is 2.05 fb^{-1}.

9.1 Comparison of the reconstructed data and Monte Carlo

The distributions of the reconstructed quantities involved in top quark charge determination, namely the distribution of b-jet and lepton $p_{\rm T}$, missing $E_{\rm T}$ and number of tracks in b-jet with $p_{\rm T} > 1$ GeV have been compared to the MC expectations normalised to 2.05 fb^{-1} of data.

It is important to investigate the b-jet charge dependence on b-jet $p_{\rm T}$. As it follows from Figure 3, the observed distribution is quite flat, only a small decrease of charge magnitude is observed with increasing jet $p_{\rm T}$. To test a agreement between the data and Monte Carlo we used scale factors defined by Equation 7.

$$S_F = \frac{\mid Q^{data}_{comb}(p_{\rm T}) \mid}{\mid Q^{MC}_{comb}(p_{\rm T}) \mid} \tag{7}$$

The scale factors for six $p_{\rm T}$ bins from 0 to 300 GeV from 3 calculated using Equation 7. The scale factor does not depend on b-jet $p_{\rm T}$ within errors and is close to one..

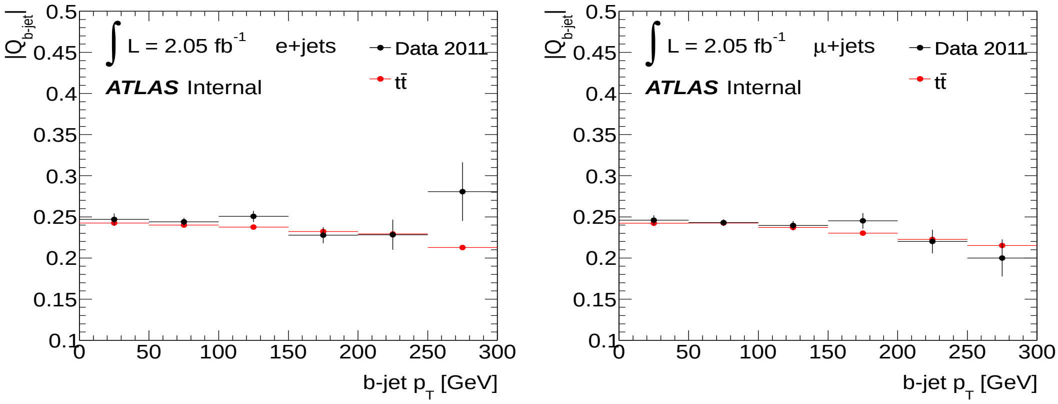

Figure 3: Comparison of the mean b-jet charge, $<\mid Q_{\rm bjet} \mid>$, as a function of b-jet $p_{\rm T}$ after the lb-pairing for electron+jets (left) and muon+jets (right) events of data and MC (MC@NLO).

The results of reconstruction of the experimental data for the integrated luminosity of 2.05 fb^{-1}, are summarised in Table 4. This table contains the number of reconstructed lepton–b-jet pairs along with the mean combined charge for the lepton+jets branch of $t\bar{t}$ events for different channels. The charge $Q_{\rm comb}$ is reconstructed in the leptonic branch of top quark decay. The $Q_{\rm comb}$ can be reconstructed also in the $t\bar{t}$

L=2.05 fb^{-1}	$< Q_{\rm comb} >$				
lepton channel	$N_{\rm expect}$	SM expected	XM expected	$N_{\rm data}$	data
$e + \mu$	3688 ± 257	-0.075 ± 0.005	0.069 ± 0.006	3914	-0.077 ± 0.005
e	1594 ± 158	-0.075 ± 0.008	0.073 ± 0.008	1638	-0.079 ± 0.008
μ	2094 ± 202	-0.074 ± 0.007	0.065 ± 0.007	2276	-0.075 ± 0.007

Table 4: Reconstructed mean combined charge, $< Q_{\rm comb} >$, for the data $t\bar{t}$ candidate events at the integrated luminosity of 2.05 fb^{-1} in different lepton+jets channels in comparison with the MC expected yield for the Standard model (SM expected) and the exotic model (XM expected) at the same value of integrated luminosity (L).

hadronic branch, where the combine charge is constructed as a product of the hadronic branch b-jet charge and a charge opposite to the lepton charge of the leptonic branch, but in this case the selection criteria leads to a lower magnitude of combined charge and thereby to a more complicated systematics. It should be noted that the errors in the expected number of events (last two lines in Table 4) are found taking into account also the uncertainty in the cross section (from 10% for the $t\bar{t}$ and single top to 100% for QCD fakes) and 3.7% uncertainty in the integrated luminosity.

From Table 4 one can conclude that the present data are in an excellent agreement with the Standard model scenario and there is also a good agreement between the observed and expected number of events.

In Figure 4 are compared the reconstructed combined charge spectra for the data $t\bar{t}$ candidate events and Monte Carlo expectations for signal and background after lb-pairing for the muon+jets (left) and electron+jets (right) final states. The plots confirm the result of Figure 3 showing that there is good correspondence between the data and MC, i.e. the jet charge weighting procedure works well.

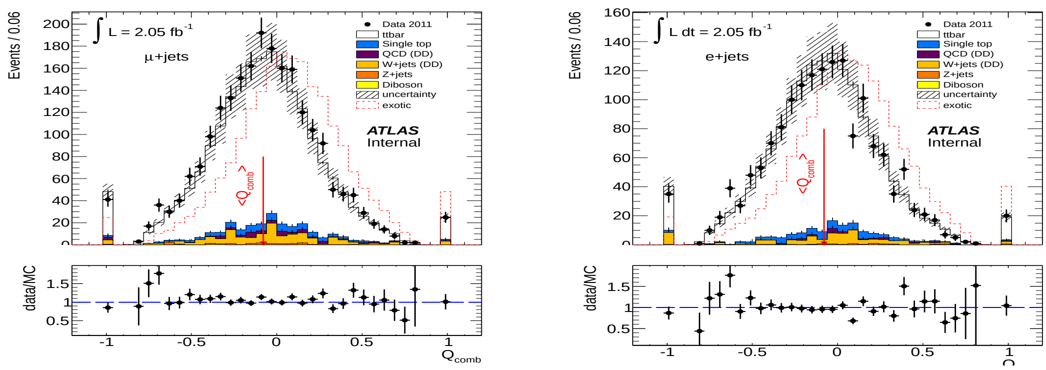

Figure 4: Distribution of combined charge, Q_{comb}, in muon + jets (left) and electron + jets (right) final states for the leptonic case.

9.2 Systematic uncertainties

The systematic studies follow the prescription described in [3]. We have calculated the systematic errors for the mean combined charge for the case when only the $t\bar{t}$ leptonic branch b-jets are taken into account.

The all considered systematic uncertainties for reconstruction of the combined charge in the electron and muon leptonic branches, as well as the combined for these two branches uncertainties, are the following:

- MC generator statistics, MC different generators, showering, top mass, ISR/FSR
- Missing E_{T}
- Jet energy scale and resolution, reconstruction efficiency
- b-tagging scale factor
- QCD, Single top, W and Z boson normalisation
- Muon efficiencies,scales and resolution
- Electron efficiencies, scales and resolution
- Pile-up

We have been evaluated the total systematics uncertainties to 15.8% in electron channel, 14.9% in muon channel and 10.9% in both together, electron+muon channel.

9.3 Statistical treatment

An important issue of the top quark charge study is the statistical credibility of the obtained result. We adopt a standard likelihood approach [17]. In our treatment we compare two hypotheses: the Standard model (null) hypothesis and the exotic model (alternative) hypothesis. The test statistic of our method, i.e. a random variable used to distinguish between the different hypotheses is the mean value of the combined charge: $Q_{\mathrm{comb}} = Q^{\ell}_{\mathrm{bjet}} \cdot Q_{\ell}$. Due to finite detector resolutions and finite size of sample, the mean value of the combined charge observed in experiment can be treated as an observation of a random variable, we will denote it $\bar{Q}$, distribution of which characterizes all possible outcomes of experiment. This variable can be expressed as

$$\bar{Q} = (1 - r_{\mathrm{b}} - r_{\mathrm{t}}) \cdot Q_{\mathrm{s}} + r_{\mathrm{b}} \cdot Q_{\mathrm{b}} + r_{\mathrm{t}} \cdot Q_{\mathrm{t}}, \tag{8}$$

where Q_{s}, Q_{b} and Q_{t} are the combined charge mean values for the signal, background and single top quark processes, respectively, and r_{b} (r_{t}) is the fraction of the background (single top quark) events in the total sample of the candidate events.

It is natural to define the SM acceptance (critical) region as $\bar{Q} < 0$ ($\bar{Q} > 0$). The decision boundary $\bar{Q} = 0$ unambiguously determines the confidence level α (probability to exclude the SM scenario if it is true) and the type II error β (a probability of failing to reject the alternative hypothesis if it is true). Quantities Q_{s}, Q_{b}, Q_{t}, r_{b} and r_{t} are the nuisance parameters of our method. We assume that the nuisance parameters are Gaussian random variables. Their mean values and uncertainties rescaled to the data integrated luminosity ($\int L\, dt$= 2.05 fb^{-1}) are summarised in Table 5 for the pp

branch	$Q_{\rm s}$	$Q_{\rm b}$	$Q_{\rm t}$	$r_{\rm b}$	$r_{\rm t}$
$e+\mu$	-0.079 $\pm$ 0.006	-0.007 $\pm$ 0.019	-0.055 $\pm$ 0.028	0.082 $\pm$ 0.012	0.041 $\pm$ 0.012
e	-0.080 $\pm$ 0.009	-0.003 $\pm$ 0.034	-0.067 $\pm$ 0.042	0.068 $\pm$ 0.015	0.043 $\pm$ 0.015
μ	-0.078 $\pm$ 0.008	-0.012 $\pm$ 0.023	-0.046 $\pm$ 0.038	0.093 $\pm$ 0.017	0.040 $\pm$ 0.017

Table 5: The nuisance parameters: the mean values and standard deviations recalculated to the integrated luminosity of the existing data sample, $\int L\,dt$= 2.05 fb^{-1}, for the leptonic branch combined charge.

center-of-mass energy of 7 TeV (in further denoted as case A) . Only b-jets from the leptonic branch of $t\bar{t}$ events are taken into account.

To understand impact of the background and systematic uncertainties for both the electron and the muon branches, alternatively were also considered the increased values of the non-top background ratio: $r_{\rm b}$=0.1 and the systematic errors to be 25% (case B).

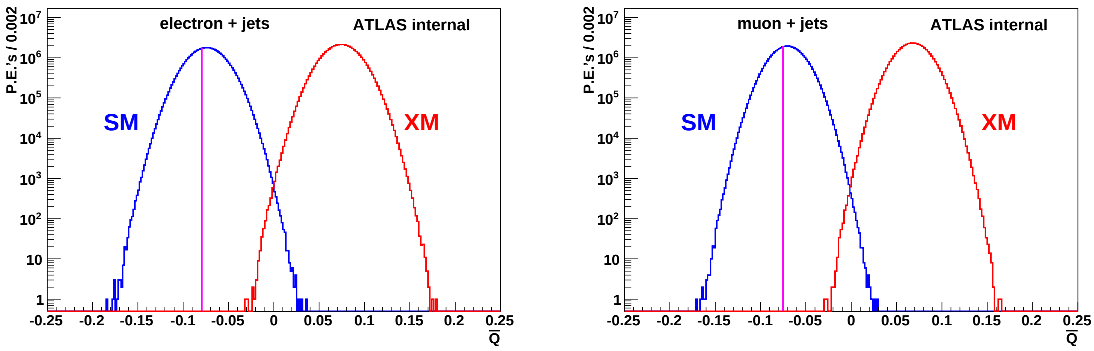

Figure 5: The $\bar{Q}$ distribution resulting from pseudo-experiments for the Standard model (blue line) and exotic (red line) hypothesis for the luminosity of 2.05 fb^{-1}, respectively. For both, the electron (left) and muon (right) case was used scale factor $S_{\rm F} = 1.00 \pm 0.19$.

One possibility to compare the two hypotheses is to calculate p-value. The p-value is the probability of obtaining a test statistic at least as extreme as the one that was actually observed provided that the null hypothesis is true. In order to obtain the p-value for the observed values of our test statistic, $< Q_{\rm comb} >$, (see Table 4), we have performed pseudo-experiments for both hypotheses, the Standard model one as well as the exotic one, and for each of the treated cases shown in Table 6.

In order to take into account a possible difference between Monte Carlo and experimental data, a scale factor, $S_{\rm F}$, defined as a ratio of the experimental and Monte Carlo mean signal combined charges. We took the $S_{\rm F}$ = 1.00 and spread σ = 0.19. The $S_{\rm F}$ uncertainty is added quadratically to the statistical and systematic error of the sampled combined mean charge.

In Figure 5 the distributions of the all possible outcomes of the ATLAS experiment expected for the observed mean combined charge ($\bar{Q}$) are shown for both hypotheses of the leptonic side reconstruction case, the SM one (blue line) and the XM one (red line), provided that the integrated luminosity is 2.05 fb^{-1}. The magenta line in these plots corresponds to the experimentally observed value Q_{obs}. The upper plots in Figure 5 correspond to the individual results for the electron and muon branches while the bottom one corresponds to their combined result.

Each of these distributions is a result of pseudo-experiments in which the nuisance parameters are sampled from the Gaussian distributions with the mean values and standard deviations taken from Table 5 and in addition to that the systematic error of the mean combined charge is added quadratically. The p-values for the Standard model and exotic cases, the distance of the observed value, Q_{obs}, from the expected value of the exotic combined charge in the XM standard deviations (S.D.) along with the quantities α and β, are summarised in Table 6 for the combined electron and muon case ($e+\mu$) as well as for the electrons (e) and muons (μ) separately, and for the above mentioned value of S_{F}. The calculations have been carried out for the expected level of background and systematics (case A) as well as for the artificially increased level (case B).

case	channel	pV_{SM}	pV_{XM}	σ_{XM}(S.D.)	α	β
A	$e+\mu$	0.746	$< 10^{-7}$	9.4	2.1×10^{-6}	3.0×10^{-6}
	e	0.772	$< 10^{-7}$	8.3	3.5×10^{-5}	3.2×10^{-5}
	μ	0.776	$< 10^{-7}$	8.3	2.0×10^{-5}	3.7×10^{-5}
B	$e+\mu$	0.725	$< 10^{-7}$	8.1	4.5×10^{-5}	6.3×10^{-5}
	e	0.719	$< 10^{-7}$	6.8	7.3×10^{-4}	6.7×10^{-4}
	μ	0.772	$< 10^{-7}$	6.6	6.3×10^{-4}	9.5×10^{-4}

Table 6: The p-values for the Standard model and exotic cases, σ_{XM} is the distance of the observed value, Q_{obs}, from the expected value of the exotic combined charge in the XM standard deviations, significance level (α) and type II error (β) for the integrated luminosity of 2.05 fb^{-1}; the case A corresponds to the standard values of nuisance parameters (see Table 5) and B to the case with the increased systematics and background ratio.

From Table 6 we conclude that at 2.05 fb^{-1} the data are in excellent agreement with the Standard model . The p-values for the Standard model scenario are high (two-sided p-value is more than 70 %) while those for the exotic hypothesis are very small (less than 10^{-7}) [2]. Converting the p-value for the $e+\mu$ case into the number of the standard deviations of the XM scenario combined charge distribution, we obtain the exclusion at the level of more than 9σ and in the individual e and μ cases more than 8σ and also in the case B with the increased level of background and systematics, the exclusion is over 6σ even for the individual e and μ cases.

[2]Outcome of none of 50 millions pseudo-experiments, assuming the exotic hypothesis, fell beyond the observed value of the mean combined charge.

10 Reconstructed top quark charge

The direct reconstruction of the top quark charge can be done relying on the obtained value of Q_{comb} from data sample of 2.05 fb^{-1} and b-jet charge calibration coefficient obtained by MC. Using the SM value of the value of the b quark charge ($Q_b = -1/3$) and the mean reconstructed value of the b-jet charge (Q_{comb}) for signal events using the invariant mass matching, the b-jet charge calibration coefficient $C_b = Q_b/Q_{comb}$ have been calculated. The top quark charge then can be calculated by using:

$$Q_{top} = 1 + C_b \times Q_{comb} \tag{9}$$

The results are shown in Table 7. The reconstructed top quark charge $< Q_{top} >$ is in very good agreement with SM prediction of 2/3e.

channel	$< Q_{top} >$	C_b
e	0.627 ± 0.041 (stat) ± 0.099 (syst)	4.296
μ	0.648 ± 0.035 (stat) ± 0.096 (syst)	4.155

Table 7: The reconstructed mean top quark charges.

The final value of top quark charge obtained by combining electron and muon channel is $Q_{top} = 0.639 \pm 0.027\ (stat) \pm 0.070\ (syst)$. The statistical error assumes that the relative error of C_b is the same as that of Q_{comb}. For the systematic error determination (see Sec. 9.2) the mean b-jet charge systematic was taken into account.

Summary

In the present work I have studied the top quark charge using the data accumulated by the ATLAS experiment at the center of mass energy of 7 TeV. The data sample of 2.05 fb^{-1} has been analysed and compared with MC.

Our main goal was to decide if the measured top quark charge is the SM or the exotic scenario quark. According the SM, the reconstructed top quark charge should be equal to 2/3e while in exotic case the charge should be equal to -4/3e. The reconstruction of top quark charge was done in the following steps:

- determination of the b-jet charge through the track charge weighting technique
- determination of the W boson charge through charge of the lepton from its leptonic decay
- pairing the W boson and b-jet originating from the same top quark

We carried out an improvement the b-jet charge algorithm. It was done by tuning a subset of parameters to maximize the efficiency of analysis (this work has been partially done at center-of-mass energy equal to 10 TeV):

- number of tracks belonging to a b-jet: minimal = 2 and maximal = 10

- study of different b-tagging algorithms with regard to determination b-jet charge: JetFitterCombNN with the threshold weight of 0.35
- the maximal size of the cone between a b-jet and track belonging to this b-jet: 0.25
- critical mass (threshold in the invariant mass criterion): 155 GeV

We have been calculated the background contribution using the dedicated MC samples and data driven method.

The mean combined charge in electron+muon channel from real data is -0.077 ± 0.005 while the expected value for SM is -0.075 ± 0.005 and for XM is 0.069 ± 0.006 what is an excellent confirmation of the SM scenario.

We have been evaluated the systematics uncertainties to 15.8% in electron channel, 14.9% in muon channel and 10.9% in both together, electron+muon channel. We use a statistical treatment to find exclusion limits for the exotic scenario. The p-values for the Standard Model scenario are more than 70% (two-sided) while those for the exotic hypothesis are less than 10^{-7}.

The analysed data give high preference to the Standard model and excludes the Exotic model at more than 5σ level if we express the difference between the observed value of the combined charge, $Q_{\rm obs}$, and the expected value of the exotic combined charge in the XM standard deviations. This result means that the exotic model is experimentally excluded.

The direct reconstruction of the top quark charge $Q_{top} = 0.639 \pm 0.027$ $(stat) \pm 0.070$ $(syst)$ was done. The result is in very good agreement with SM.

References

[1] M Baak, C Guyot, M Hauschild, R Hawkings, B Heinemann, A Höcker, M Martínez-Pérez, D Malon, P Onyisi, and E Torrence. Data quality status flags and good run lists for physics analysis in atlas. Technical Report ATL-COM-GEN-2009-015, CERN, Geneva, Mar 2009.

[2] ATLAS Coll. *Mis-identified lepton backgrounds in top quark pair production studies for EPS 2011*, 2011. ATL-COM-PHYS-2011-768.

[3] ATLAS Collaboration. Prescriptions for evaluation of systematic uncertainties.

[4] E. Ma D. Chang, W.F. Chang. *Phys. Rev. D*, 59:091503, 1999.

[5] A. Abulencia et al. First cdfmeasurement ot the topquark charge using the top decay products. 2007. CDF Note 8783.

[6] G.Corcella et al. *JHEP*, 0101:010, 2001.

[7] M.L. Mangano et al. *JHEP*, 0307:001, 2003.

[8] R. Barate et al. Determination of A(b)(FB) using jet charge measurements in Z decays. *Phys. Lett.*, B426:217–230, 1998.

[9] S. Frixione et al. *JHEP*, 0206:029, 2002.

[10] V. M. Abazov et al. *Phys. Rev. Lett.*, 98:041801, 2007.

[11] S. Abachi et al. (D0 collaboration). *Phys. Rev. Lett.*, 74:2632, 1995.

[12] Abe et al.(CDF collaboration). *Phys. Rev. Lett.*, 74:2626, 1995.

[13] M.H.Seymour J.M.Butterworth, J.R.Forshaw. Multiparton interactions in photoproduction at hera. (CERN-TH/95-82, MC-TH-96/05, UCL/HEP 96-02), 1996. arXiv:hep-ph/9601371v1.

[14] B.P. Kersevan and E. Richter-Was. *The Monte Carlo Event Generator AcerMC version 3.4 with interfaces to PYTHIA 6.3, HERWIG 6.5 and ARIADNE 4.1*, 2004.

[15] R.D.Field and R.P.Feynman. A parameterization of the properties of quark jets. *Nucl. Phys.*, B136:1–76, 1978.

[16] P. Skands T. Sjostrand, S. Mrenna. Pythia 6.4: Physics and manual, 2006. hep-ph/0603175.

[17] J. Conrad W.A. Rolke, A.M. Lopez. *Nucl. Instr. Meth.*, A551:493, 2005.

List of articles related to the PhD thesis

1. ATLAS Collaboration, Measurement of the top quark pair production cross section in pp collisions at root s=7 TeV in dilepton final states with ATLAS, Physics Letters B. - Vol. 707, No. 5 (2012), p. 459-477
2. ATLAS Collaboration, Measurement of the top quark pair production cross section with ATLAS in pp collisions at root s=7 TeV, The European Physical Journal C - Particles and Fields. - Vol. 71, No. 3 (2011), Art. No. 1577, p. 1-36
3. ATLAS Collaboration, Performance of the ATLAS detector using first collision data, Journal of High Energy Physics. - No. 9 (2010), Art. No. 056, p. 1-62
4. ATLAS Collaboration, Expected performance of the ATLAS experiment: TOP QUARK PROPERTIES, CERN, 2009. - p. 1003-1037. - (CERN-OPEN-2008-020)

List of conference articles related to the PhD thesis

1. Pavol Federič, The study of the top quark electric charge at the ATLAS experiment, Študentská vedecká konferencia FMFI UK, Bratislava 2010: Zborník príspevkov., p. 202-206. - ISBN 978-80-89186-68-6

Contributions at international conferences related to the PhD thesis

1. Pavol Federič, Measurement of the top quark electric charge in the ATLAS experiment, TOP 2011 - 4th International Workshop on Top Quark Physics, September 25-30, 2011, Spain