DØ Note 4876-CONF

Measurement of the charge of the top quark with the DØ experiment

The DØ Collaboration
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We present a measurement of the top quark charge using data collected by the DØ Run II experiment at the Fermilab Tevatron $p\bar{p}$ collider at $\sqrt{s}$=1.96 TeV. We use top-antitop quark pairs ($t\bar{t}$) found in events in data samples corresponding to an integrated luminosity of 366 pb^{-1} (363 pb^{-1}) in the e+jets (μ+jets) final state. We select 17 events in data with a high p_T electron or muon and at least four jets, two of which must be b-tagged by having an associated secondary vertex. We apply a jet charge algorithm to the secondary vertex tagged jets to discriminate between b- and $\bar{b}$-jets. The performance of the algorithm is calibrated using $b\bar{b}$ pairs from data. A constrained kinematic fit is performed to reconstruct the $t\bar{t}$ event. We find that the data are in good agreement with a top quark charge of $2e/3$, as assumed in the standard model, and we exclude the hypothesis of an exotic quark with charge $4e/3$ at 94% confidence level.

Preliminary Results for Autumn 2005 Conferences

I. INTRODUCTION

It is widely believed that the heavy particle discovered by the CDF and DØ Collaborations at the Tevatron collider in 1995 [1] is the long-sought top quark. The currently measured properties of the particle are consistent with standard model (SM) expectations for the top quark, but many of its properties are still only poorly known. In particular, the electric charge, which is a fundamental quantity characterizing a particle, has not been measured for the top quark yet. It still remains not only to confirm that the discovered quark has charge $2e/3$ as predicted by the SM, but also to measure the strength of its electromagnetic (EM) coupling to rule out anomalous contributions to its EM interactions. Furthermore, it is possible to interpret the discovered particle as either a charge $2e/3$ or $-4e/3$ quark. In the published top quark analyses of the CDF and DØ Collaborations [2], the correlations of the b-quarks and the W-bosons in $p\bar{p} \rightarrow t\bar{t} \rightarrow W^+W^-b\bar{b}$ are not uniquely determined. As a result, there is a twofold ambiguity in the pairing of W bosons and b-quarks, and, consequently, in the electric charge assignment of the "top quark". In addition to the SM assignment, $t \rightarrow W^+b$, $''t'' \rightarrow W^-b$ is also conceivable, in which case the top quark would actually be an exotic quark with charge $q= -4e/3$. Current $Z \rightarrow \ell^+\ell^-$ and $Z \rightarrow b\bar{b}$ data can be fitted with a top quark of mass m_t =270 GeV, provided that the right-handed b-quark mixes with the isospin $+1/2$ component of an exotic doublet of charge -1$e/3$ and $-4e/3$ quarks, $(Q1\ ,Q4)_R$ [3]. In this scenario, the $-4e/3$ charge quark is the particle discovered at the Tevatron, and the top quark, with mass of 270 GeV, would have so far escaped detection. We assume that constraints arising from flavor mixing measurements are compatible with this scenario.

In this paper, we report the first measurement of the top quark charge. We use the *lepton* (electron or muon) plus jets channel using b-jet identification (b-tagging) techniques exploiting the long lifetime of b-hadrons. The data were collected by the DØ experiment from June 2002 through August 2004, and correspond to an integrated luminosity of 366 pb^{-1} (363 pb^{-1}) in the electron (muon) sample.

The experimental procedure chosen here to rule out one of the hypotheses comprises three steps. The first step is to select a pure sample of $t\bar{t}$ events in data, with an isolated lepton with high transverse momentum (p_T), large missing transverse energy ($\not{E}_T$), and four or more jets. To this end, we consider only events with at least two lifetime-tagged jets. Each of the selected $t\bar{t}$ events has two "legs", one with a leptonically decaying W ($t \rightarrow Wb \rightarrow \ell\nu b$) and one with a hadronically decaying W ($t \rightarrow Wb \rightarrow q\bar{q}^{'}b$).

The second step of the analysis consists in assigning the correct jets and leptons to the correct "leg" of the event, so that we know which b-jet comes from the same top (or anti-top) quark as the lepton. To make this assignement we perform a constrained kinematic fit. In each $t\bar{t}$ event we compute our observable Q which is the sum of the lepton charge from the W boson decay and the charge of the b-jet associated to the same leg as the lepton by the kinematical fit. We compute the charge of the b-jet using a jet charge algorithm calibrated from data. The goal of the present analysis is to discriminate between the standard model hypothesis Q_{top}=$+2e/3$ and the exotic hypothesis $Q_{``top''} = -4e/3$. Because of charge conservation, measuring the absolute value of the charge $|Q|$ does not lead to any loss of information since every event contains one top and one anti-top quark. This also allows us to measure the top quark charge twice in every event. The third step is to use the shape of the jet charge (defined in section IV) for b-jets in data to derive the expected shape of $|Q|$ for the SM and the exotic scenarios. The jet charge distributions for top quarks are mixed with charge distributions expected for the small background contribution to the sample. The distribution of $|Q|$ is then compared with the data and a likelihood method is used to discriminate between the two scenarios.

II. THE DØ DETECTOR

The DØ detector includes a tracking system, calorimeters, and a muon spectrometer [4]. The tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located inside a 2 T superconducting solenoid. The tracker design provides efficient charged particle measurements in the pseudorapidity region $|\eta| < 3$ [5]. The SMT strip pitch of 50–80 μm allows a precise reconstruction of the primary interaction vertex (PV) and an accurate determination of the impact parameter of a track relative to the PV [6], which are the key components of the lifetime-based b-jet tagging algorithm. The Secondary Vertex Tagging (SVT) used in this analysis relies on the presence of a secondary vertex significantly distant from the primary interaction vertex (PV). The PV is required to be within the SMT fiducial volume and consists of at least 3 tracks. The calorimeter consists of a central section (CC) covering $|\eta| < 1.1$, and two end calorimeters (EC) extending the coverage to $|\eta| \approx 4.2$. The muon system surrounds the calorimeter and consists of three layers of tracking detectors and two layers of scintillators [7]. A 1.8 T iron toroidal magnet is located outside the innermost layer of the muon detector. The luminosity is calculated from the rate for $p\bar{p}$ inelastic collisions detected using two hodoscopes of scintillation counters mounted close to the beam pipe on the front surfaces of the EC calorimeters.

III. EVENT SELECTIONS

We select data samples in the electron and muon channels by requiring an isolated electron with $p_T > 20$ GeV and $|\eta| < 1.1$, or an isolated muon with $p_T > 20$ GeV and $|\eta| < 2.0$. More details on the lepton identification as well as trigger requirements are reported elsewhere [8]. In both channels, we require $\not{E}_T$ to exceed 20 GeV and not be collinear with the lepton direction in the transverse plane. These W boson candidate events must be accompanied by four or more jets with $p_T > 15$ GeV and rapidity $|y| < 2.5$. Jets are defined using a cone algorithm with radius $\Delta\mathcal{R} = 0.5$ [9]. By requiring events with at least two b-tagged jets, we are able to significantly enhance the $t\bar{t}$ to background ratio.

Secondary vertices are reconstructed from two or more tracks satisfying the following requirements: $p_T > 1$ GeV, ≥ 1 hits in the SMT layers and impact parameter significance $d_{ca}/\sigma_{d_{ca}} > 3.5$. Tracks identified as arising from K^0_S or Λ decays or from γ conversions are not considered. If the secondary vertex reconstructed within a jet has a decay length significance $L_{xy}/\sigma_{L_{xy}} > 7$ [10], the jet is declared SVT-tagged as a b-quark jet. Events with at least two tagged jets are referred to as double-tag events. A description of how b-tagging, c-tagging and light-jet tagging efficiencies are computed can be found in Ref. [16] along with a description of the procedure used to calculate the event tagging probabilities for the background processes and for $t\bar{t}$ events.

The main background is the direct production of W bosons in association with jets (W+jets), with the W boson decaying leptonically. In most cases, the jets accompanying the W boson originate from light (u,d,s) quarks and gluons (W+light jets). Depending on the jet multiplicity, between 2% and 14% of W+jets events contain heavy flavor jets resulting from gluon splitting into $b\bar{b}$ and $c\bar{c}$ ($Wb\bar{b}$ or $Wc\bar{c}$, respectively). In this analysis the requirement of at least two SVT-tagged jets suppresses all the backgrounds except $Wb\bar{b}$ which is expected to represent ∼5% of the sample. The second largest source of background is single top production, which is expected to contribute around 1% of the selected events.

IV. JET CHARGE ALGORITHM

Discrimination between b- and $\bar{b}$ jets is achieved by using the tracks of charged particles inside the SVT-tagged jets. The track momenta and charge are measured with the DØ central tracking system. We use all tracks within a cone of $\Delta\mathcal{R}$=0.5 [12] from the SVT-tagged jet axis. The tracks must have $p_T > 0.5$ GeV and be within 0.1 cm of the primary vertex in the z-direction (along the beam axis). The jet charge q_{jet} is defined as the p_T weighted average of the track momenta

$$q_{jet} = \frac{\sum_i q_i \cdot p_{T_i}^{0.6}}{\sum_i p_{T_i}^{0.6}} \qquad (1)$$

where the subscript i runs over the selected tracks. The chosen values for the exponent (0.6) in equation 1 and for the jet cone size are the result of an optimization using fully simulated Monte Carlo $t\bar{t}$ events. The discriminating power for b- versus $\bar{b}$-jets and the jet charge distributions are directly derived from $b\bar{b}$ data. The jet charge distributions are then applied to $t\bar{t}$ Monte Carlo, in order to predict the expected distribution of top quark charge. There are important differences, in particular in the η and p_T distributions, between b-jets in $b\bar{b}$ data and b-jets in $t\bar{t}$ events. These differences are taken into account and result in the dominant systematic uncertainties for this measurement.

A. Calibration of the jet charge algorithm using $b\bar{b}$ data

We derive the shape of the jet charge distributions for b- and $\bar{b}$-jets from data. A $b\bar{b}$ data sample is selected by requiring events with exactly two jets j_1 and j_2, both being SVT-tagged, with $p_T > 15$ GeV and within $|y|$ <2.5, with an azimuthal distance $\Delta\phi(j_1, j_2)$ larger than 3.0. In addition we require that one jet (j_1) contains a muon with $p_T >$ 4 GeV. We refer to j_1 as the "tag jet" and to j_2 as the "probe jet".

The probe jet is the jet from which we derive the jet charge distribution. The production of a b-quark can occur via flavor creation, flavor excitation or gluon splitting. Since j_1 and j_2 are chosen back-to-back in our selected $b\bar{b}$ sample, we assume that the $b\bar{b}$ sample is dominated by flavor creation [13–15] and assign a systematic uncertainty to this assumption by varying the $\Delta\phi(j_1, j_2)$ cut between 2.65 and 3.0 (thus varying the fraction of flavor creation from about 80% to about 95%) and propagating the resulting effect to the final top quark charge distribution.

The charge of the muon inside the tag jet is correlated with the type of quark (b or $\bar{b}$) on the probe jet side. The correlation is less than 100% and a number of experimental corrections must be applied. In practice, if we take the jet charge distributions of the probe jets in events with a positive muon we obtain a jet charge distribution which is a mixture of about 66% of the b-jet charge distribution, 28% of the $\bar{b}$-jet charge distribution and 6% of $\bar{c}$-jet charge

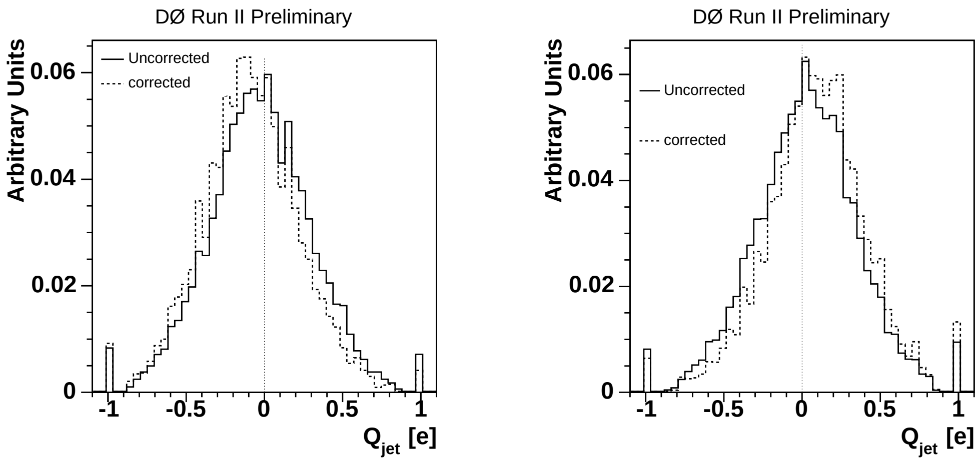

FIG. 1: Normalized b (left) and $\bar{b}$-jet charge (right) distributions before and after c-jets and B-mixing corrections.

distribution. In the next section, we describe how we extract the pure b- and $\bar{b}$-jet charge distribution from this sample.

B. Corrections to the jet charge distributions from data

To determine the fraction of c-jets in the sample, we study the spectrum of the muon transverse momentum with respect to the jet axis (p_T^{rel}). We fit the p_T^{rel} distribution observed in the $b\bar{b}$ sample with a sum of two p_T^{rel} templates, one for b-jets (including both prompt and cascade decays) and one for semi-muonic decays inside c-jets. We assume that the fraction of light-flavor jets is negligible. We find that the fraction of c-jets is $6\pm2\%$. Given that the light-jet tagging probability is $\sim$15 times lower than for c- jets [11], this confirms *a posteriori* the assumption that the light-quark fraction is negligible.

To correct for the c-jet contribution we derive a correction function as a ratio of two Monte Carlo quantities: the jet charge distributions for pure b-jets divided by the jet charge distribution obtained by mixing 94% of b-jet charge and 6% of c-jet charge. The uncertainty on the c-fraction and the statistical uncertainties on the shape of the correction are taken as systematic uncertainties.

The tagging muons in the $b\bar{b}$ data sample can come from a cascade decay of a B-meson rather than its direct decay. The B-meson might also have oscillated to its anti-particle destroying the correlation between the sign of the tagging muon and the type of b-quark (b or $\bar{b}$) initiating the probe jet. To correct for this effect, we consider the amount of muons coming from cascade decays in $Z \to b\bar{b}$ Monte Carlo and the amount of B-mixing in the Monte Carlo. In the same spirit as for the c-correction, we derive a correction that is the ratio of two Monte Carlo-based quantities and apply it to the jet charge distribution from the $b\bar{b}$ data sample after it has been corrected for c-jets. Figure 1 shows the jet charge distributions for b- and $\bar{b}$-jets before and after corrections. The b- and $\bar{b}$-jet distributions are normalized to an area of one and can be interpreted as the probability density functions to measure a certain jet charge Q given the type of quark (b or $\bar{b}$) initiating the jet. We denote these probability density functions $f_b(Q)$ and $f_{\bar{b}}(Q)$. We assign systematic uncertainties to the rate at which the muon charge swaps with respect to the original b- or $\bar{b}$-quark due to cascade, B-mixing and charge misidentification of the measured tagging muon. We also take into account the kinematical differences between b-jets in $b\bar{b}$ data and in $t\bar{t}$ events and assign systematic uncertainties due to these differences.

V. TOP CHARGE TEMPLATES

In order to measure the top quark charge, we need an observable and an expectation for that observable in the case $|Q_{top}|$ =$2e/3$ and in the case $|Q_{``top''}|$ =$4e/3$. The expectation for the observable is necessary in order to be able to determine the confidence level of the measurement. We will refer to the $2e/3$ and $4e/3$ cases as the SM and the exotic (EX) scenario respectively.

A. Template Determination

In the previous section, we determined the expected shapes of jet charge for b-jet and $\bar{b}$-jets in data. We use them here to form distributions of the reconstructed charges in case of a SM top and of an exotic top.

Since there are two top quarks in each event, the top quark charge can be measured twice per event. One top quark charge is constructed as the sum of the charge of the lepton (e or μ) and the jet charge of the b-jet from the same top quark. The second top quark charge is constructed as the sum of the second b-jet charge *minus* the charge of the charged lepton. The two observables in each event are defined as:

$$\begin{aligned} Q_1 &= |q_\ell + q_b| \\ Q_2 &= |-q_\ell + q_B| \end{aligned} \tag{2}$$

where q_ℓ is the charge of the charged lepton, q_b is the charge of the b-jet on the leptonic leg of the event (j_b) and q_B is the charge of the b-jet on the hadronic leg of the event (j_B).

In the present analysis we assume that the top quark decays 100% of the time to a W-boson and a b-quark. Therefore the final state of a $t\bar{t}$ event contains at least two b-jets and the decay of the two W-bosons. In this analysis we consider only the $\ell + jets$ final states. This means that one W-boson decays hadronically and one W-boson decays leptonically. In total there are at least four jets (two from the hadronic W-boson decay). One should note that the W-boson decay can lead to a c-jet, and that the SVT-tagged jets are not purely b-jets. The top quark charge observables Q_1 and Q_2 are produced using a constrained kinematic fit for the $t\bar{t}$ hypothesis with the top mass fixed at 175 GeV to determine the association of the two b-jets to the W-bosons. We find that the best kinematic fit gives the correct assignment in 78.8±1.8% of the cases.The kinematic fit considers all jets in the event. Events with more than four jets arise due to initial or final state radiation.

We derive the expected shapes of the top quark charge distributions Q_1 and Q_2 from $t\bar{t}$ Monte Carlo and the b- and $\bar{b}$-jet charge distributions derived from data in the previous section. By using jet-parton matching the true flavor of the jets j_b and j_B can be found. If the true flavor of $j_b(j_B)$ is b then the jet charge q_b (q_B) is set to one randomly chosen value according to the probability density function $f_b(Q)$ (defined in Sec. IV B). If it is a $\bar{b}$-jet then one uses the probability density function $f_{\bar{b}}(Q)$. If the true type of jet for j_b (j_B) is a c-jet then we set q_b (q_B) to a value of the c-jet charge randomly chosen from the c-jet charge probability density function, derived on Monte Carlo and similarly in case of a $\bar{c}$-jet. In a very small fraction of $t\bar{t}$ events in Monte Carlo, one of the SVT-tagged jets is a light-quark jet. In this case we choose a random value from the corresponding light-quark jet charge probability density function, derived from Monte Carlo.

The resulting distributions in the observables $Q_1 = |q_\ell + q_b|$ and $Q_2 = |-q_\ell + q_B|$ provide the SM top quark charge templates. The shape of the exotic top quark charge templates are determined by simply permuting the jet charge of the SVT-tagged jets on the leptonic and hadronic W-decay side of the event giving the two observables $Q_1 = |q_\ell + q_B|$ and $Q_2 = |-q_\ell + q_b|$. The shape of the distributions of Q_1 and Q_2 obtained in this way provide the exotic top quark charge templates. To take into account the background contamination we add to the top quark charge templates a small contribution of "top quark charge" observables determined by performing the kinematic fit on the background and using the data-derived b- and $\bar{b}$-jet charge templates. The resulting exotic and standard model templates are normalized to one and are used as probability density functions in the confidence level extraction. These probability density functions are denoted $p^{\rm ex}$ and $p^{\rm sm}$ respectively.

B. Systematic Uncertainties

Several instrumental uncertainties can affect the kinematical fit. We take into account the uncertainties due to the jet energy calibration, the jet energy resolution and the uncertainty to reconstruct a jet, especially at low p_T. In the kinematic fit we use a constraint to a top mass of 175 GeV. Nevertheless the top mass is only known to a finite precision. We rederive the top quark charge templates on samples generated with various top mass. The resulting variations in SM and exotic top quark charge distributions are taken as systematic errors. The total systematic uncertainty on the background composition is also propagated to the uncertainty on the final result. The number of background events is allowed to fluctuate according to a Binomial distribution.

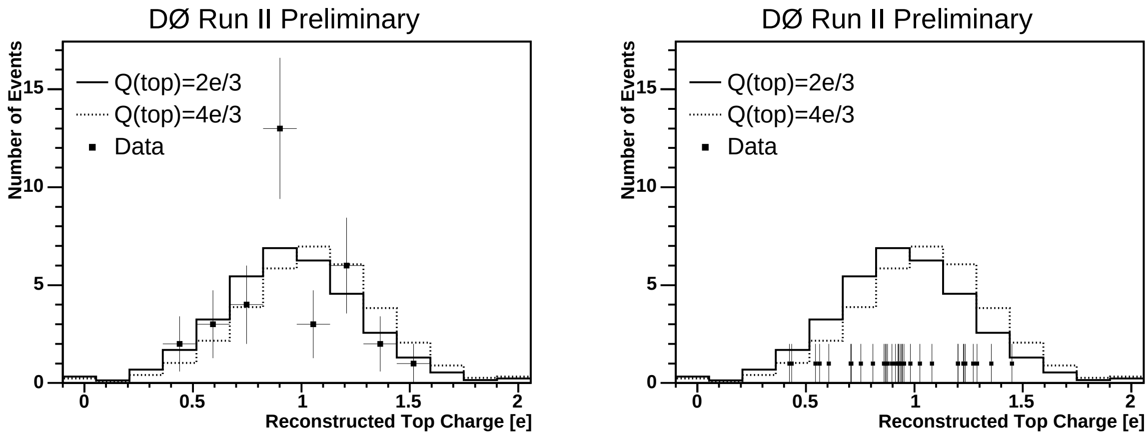

FIG. 2: The 34 measured values of the top quark charge compared to the SM and exotic scenario templates, both binned (left) and unbinned (right).

VI. RESULTS

A. Likelihood ratio test

In data, we measure the reconstructed top quark charges Q_1 and Q_2. Out of 21 selected double tag events, 17 have a kinematic fit that converged in at least one of the combinations where the two jets j_b and j_B are associated to a SVT-tagged jet. Each of the 17 events provides two measurements of the top quark charge, giving 17 observations of Q_1 and 17 observations of Q_2, i.e. a total of 34 top quark charge observations. Fig. 2 shows the measured values in data overlaid with the SM and exotic top quark charge distributions.

To test the SM and the exotic top quark charge hypothesis we perform a likelihood ratio test. We use the ratio of the likelihood of the observation assuming the standard model case divided by the likelihood of the observation assuming the exotic scenario:

$$\Lambda = \frac{\prod_i p^{\rm sm}(q_i)}{\prod_i p^{\rm ex}(q_i)} \tag{3}$$

where $p^{\rm sm}(q_i)$ is the probability to observe the top quark charge q_i in the SM scenario and $p^{\rm ex}(q_i)$ is the probability to observe the top quark charge q_i in the exotic scenario (Section V). The subscript i runs over all 34 available measurements in data of the top quark charge. We obtain:

$$\Lambda^{\rm data} = 11.5$$

B. Generation of pseudo-experiments in the Standard Model and Exotic Scenarios

The value of $\Lambda^{\rm data}$ is compared to the distributions of expected $\Lambda^{\rm sm}$ and $\Lambda^{\rm ex}$ obtained by generating pseudo-experiments to emulate the SM and exotic cases, respectively.

We obtain the distribution of $\Lambda^{\rm sm}$ by generating pseudo-experiments in the following way. We allow the signal and background fraction to fluctuate according to their errors. The number of background events, N_{bkg}, is obtained from a binomial distribution with a mean value at the central prediction of the background fraction. The systematic uncertainties are modeled using nuisance parameters [17] and the shapes of the distributions $p^{\rm sm}(q)$ and $p^{\rm ex}(q)$ are functions of the nuisance parameters. For each ensemble we draw random values of the nuisance parameters and rederive the shape of the SM and exotic templates. Since in the data we have 34 measurements of the top quark charge, we sample the top quark charge distribution $p^{\rm sm}(q)$ 34-N_{bkg} times, and the background template N_{bkg} times, to obtain a set of 34 pseudo-observations. For this set of pseudo-observations we compute the likelihood ratio Λ. We

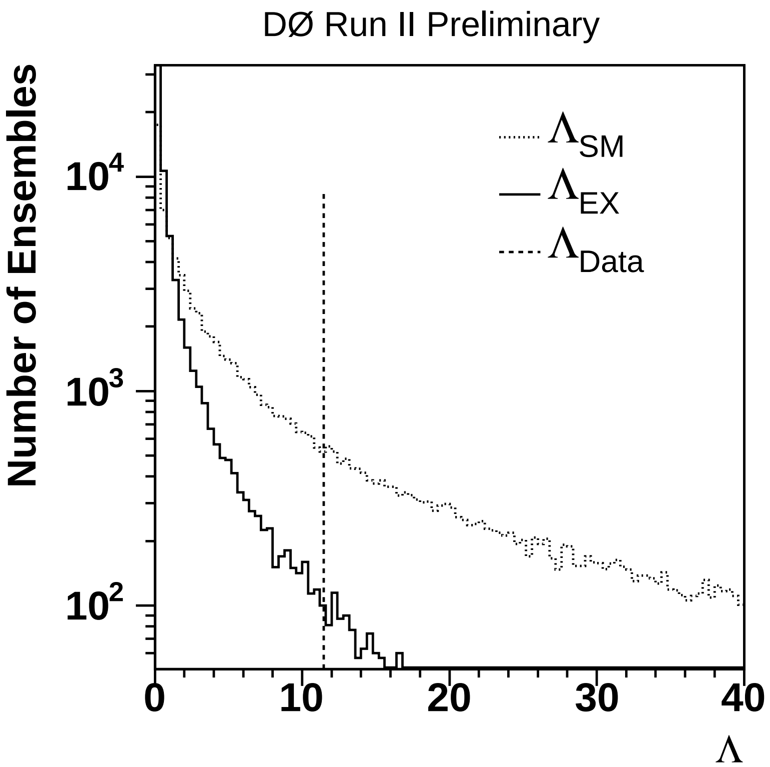

FIG. 3: Likelihood ratio distributions for a SM top quark $\Lambda^{\rm sm}$ or an exotic top quark $\Lambda^{\rm ex}$ with systematics taken into account. The measured value of $\Lambda^{\rm data}$ is shown as a vertical dashed line.

repeat this procedure 100,000 times to obtain the distribution of the likelihood ratio Λ_{sm} that is expected in case of a SM top quark.

The same procedure is applied to derive the distribution of likelihood ratio $\Lambda^{\rm ex}$ expected in case of an exotic top quark. The distributions of $\Lambda^{\rm ex}$ and $\Lambda^{\rm sm}$ taken into account the systematic uncertainties are shown in Fig. 3 together with the value $\Lambda^{\rm data}$ observed in data.

C. Confidence level

1. *Observed Confidence Level*

Figure 3 shows that the observation Λ^{data} is more likely if the data contains SM top quarks rather than exotic top quark. We compute that the probability for the exotic case to give $\Lambda > \Lambda^{\rm data}$ is only 6.3% , giving an exclusion of the $4e/3$ scenario at 93.7%. The effect of including systematic uncertainties in the confidence level calculation is given in table I.

2. *Expected Confidence Level*

If we define the expected confidence level as the probability for the exotic scenario to fluctuate above the median value of the SM expectation we obtain an expected confidence level of 89.0% C.L. We also quantify the consistency with the SM expectation by computing the probability for the SM to give an outcome $\Lambda^{\rm sm} > \Lambda^{\rm data}$. This probability is 34.0%. Therefore the observation is in agreement with the SM expectation.

Source	Predicted C.L.	Observed C.L.
Stat. only.	96.9	98.7
+ Jet energy resolution	96.9	98.5
+ Jet energy calibration	97.0	98.6
+ Jet reconstruction	96.6	98.3
+ Jet charge corrections	94.9	97.4
+ b-jet production meachanism	94.5	97.0
+ η spectrum of b-jets	93.8	96.6
+ Top mass	92.4	96.1
+ p_T spectrum of b-jets	89.0	93.7

TABLE I: Summary of the systematic uncertainties and their accumulating effect on the observed and expected confidence level. The systematic uncertainties called η- and p_T spectrum of b-jets refers to the systematic uncertainties assigned to take into account the kinematical differences between the $b\bar{b}$ data sample and $t\bar{t}$ Monte Carlo. Jet charge corrections refers to the systematic uncertainties from limited Monte Carlo statistics, c-fraction and the uncertainty in Monte Carlo of the fraction of muon charge swaps in our data calibration method.

VII. CONCLUSION

We present the first measurement of the charge of the top quark charge, using $p\bar{p}$ data collected by the DØ experiment. We select a pure $t\bar{t}$ sample by choosing lepton (electron or muon) plus four jet events with two secondary vertex tagged jets in a dataset corresponding to an integrated luminosity of 366 pb^{-1} (363 pb^{-1}) in the electron (muon) sample. A jet charge algorithm is used to discriminate between b- and $\bar{b}$- jets. The performance of the algorithm is determined in a $b\bar{b}$ data sample. We perform a likelihood ratio test to discriminate between the $2e/3$ and $4e/3$ hypotheses for the top quark charge. The possibility that the top quark charge is $4e/3$ is ruled out to a confidence level of 94% . The observed top quark charge distribution is in good agreement with the standard model.

VIII. ACKNOWLEDGMENTS

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[4] DØ Collaboration, V. Abazov *et al.*, "The Upgraded DØ Detector", in preparation for submission to Nucl. Instrum. Methods Phys. Res. A..
[5] Rapidity y and pseudorapidity η are defined as functions of the polar angle θ and parameter β as $y(\theta,\beta) = \frac{1}{2}ln(\frac{1+\beta cos\theta}{1-\beta cos\theta})$ and $\eta(\theta) = y(\theta, 1)$, where β is the ratio of a particle's momentum to its energy.
[6] Impact parameter is defined as the distance of closest approach (d_{ca}) of the track to the primary vertex in the plane transverse to the beamline. Impact parameter significance is defined as $d_{ca}/\sigma_{d_{ca}}$, where $\sigma_{d_{ca}}$ is the uncertainty on d_{ca}.
[7] V. Abazov *et al.*, FERMILAB-PUB-05-034-E (2005).
[8] DØ Collaboration, V. Abazov *et al.*, hep-ex/0504043.
[9] We use the iterative, seed-based cone algorithm including midpoints, as described on p. 47 in G. C. Blazey *et al.* , in Proceedings of the Workshop: *"QCD and Weak Boson Physics in Run II"*, edited by U. Baur, R. K. Ellis, and D. Zeppenfeld, FERMILAB-PUB-00-297 (2000).
[10] Decay length L_{xy} is defined as the distance from the primary to the secondary vertex in the plane transverse to the beamline. Decay length significance is defined as $L_{xy}/\sigma_{L_{xy}}$, where $\sigma_{L_{xy}}$ is the uncertainty on L_{xy}.
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