CDF note 10460

The CDF Measurement of the Top Quark Charge using the Top Decay Products in Lepton+Jet channel

The CDF Collaboration
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We report on the measurement of the top quark charge using the decay products of the top quark. There are three main components to this measurement: determining the charge of the W (using the charge of the lepton), pairing the W with the b jet to ensure that they are from the same top decay branch and finally getting the flavor of the b jet using the Jet Charge algorithm. Using 5.6fb^{-1} of data we found the result to be consistent with the standard model, while excluding an exotic quark hypothesis with 99% confidence.

Preliminary Results for Summer 2011 Conferences

I. INTRODUCTION

Since the discovery of the top quark, CDF has measured several properties of those events to confirm that the top quark has the properties expected in the standard model (SM). Determining whether the top quark decays into a W^+ and a bottom quark while the anti-top quark decays to a W^- and an anti-bottom quark would ensure indirectly that the charge of the top quark is indeed $+2/3$ as is the charge of the top quark in the standard model. If these events were found to have an object decaying to a W^- and a bottom quark, the charge of this object would be $-4/3$ and would not correspond to the standard model top quark. Such an hypothesis has been put forward [1] and proposes that this new particle would be an exotic quark, part of a fourth generation of quarks and leptons. These authors also calculate that the standard model top quark would be at a mass > 230 GeV/c^2. Exclusion of the exotic top quark hypothesis has been presented, [2–4] , with less data or less sensitivity then the present measurement.

There are three main ingredients to this analysis: determining the charge of the W (using the charge of the lepton), pairing the W with the b jet to ensure that they are from the same top decay branch and finally getting the flavor of the b jet using the Jet Charge algorithm. We assemble these ingredients such that events where the charge of the lepton is opposite to the Jet Charge value are assigned to the SM hypothesis while events where the charge of the lepton is of the same sign as the Jet Charge value are assigned to the exotic quark hypothesis. We describe each ingredient in turn. First we describe the data sample and event selection. The CDF detector is described in detail in [5].

II. DATA SAMPLE & EVENT SELECTION

This analysis is based on an integrated luminosity of 5.6fb^{-1} collected with the CDFII detector between March 2002 and February 2010. The data are collected with an inclusive lepton trigger that requires an electron or muon with E_T >18 GeV (P_T >18 GeV/c for the muon). From this inclusive lepton dataset we select events offline with a reconstructed isolated electron E_T (muon P_T) greater than 20 GeV, missing $E_T(MET)$ >20 GeV and at least 3 jets with E_T >20 GeV and $|\eta| < 2.0$ in addition to a fourth jet with $E_T > 12$ GeV and $|\eta| < 2.4$.

The muon acceptance is increased by including events with non-triggered leptons. Such events are required to have at the trigger level a missing transverse energy larger than 35 GeV and at least two jets of $E_T > 10$ GeV. Candidates are selected if they contain a CMX track segment in a region not covered by the inclusive lepton trigger, or a track segment only in the CMU (CMP) chamber or an isolated track not fiducial to any muon detector. Muons in these categories, called "extended muons", are also required to pass the isolation cut and to have $p_T > 20$ GeV. In addition, and to ensure full efficiency of the trigger, these events require at least two jets with $E_T > 25\,GeV$, one of which should be central ($|\eta| < 0.9$) and separated by $\Delta R_{jj} > 1.0$.

The dataset selected above, called "lepton+jets" (LJ), is dominated by QCD production of W bosons with multiple jets. To improve the signal to background we identify events with two or more b jets by requiring that the jets contain a secondary vertex, characteristic of a B hadron having decayed. This secondary vertex algorithm is tuned such that the efficiency of identifying a b jet is about 50% while the efficiency of misidentifying a light quark is about 2%. More information about the algorithm used can be found in [6, 7].

III. PAIRING BETWEEN THE W AND THE b JET

In order to pair the identified lepton with the right b jet we make use of the top mass kinematic fitter which evaluates a χ^2 containing the constraints on top quark mass (we use a value of 172.5 GeV/c^2) and W mass for each combination. Since we have identified the 2 b jets in the event using the secondary vertex algorithm, there are only 2 possible combinations and 4 χ^2 values per event (the factor of 2 is because of the unknown z component of the neutrino). By keeping events where the lowest χ^2 is less than 9 and by picking the combination corresponding to the lowest χ^2, we obtain a selection efficiency of 53% and a purity of 83%.

IV. FLAVOR TAGGING THE b JET

In order to determine whether the high p_T b jet characteristic of a $t\bar{t}$ event comes from a b quark or a $\bar{b}$ quark, we make use of the Jet Charge (JetQ) algorithm. We select good tracks (for example the track impact parameter is less than 0.15 cm and the track p_T is larger than 1.5 GeV/c) within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ less than 0.4 centered on the b jet axis. We only compute JetQ if there are at least 2 tracks within this cone. We then sum up the charges of those tracks weighting each track according to their momentum along the jet axis:

$$JetQ = \frac{\sum(\vec{p}_{track} \cdot \vec{p}_{jet})^{0.5} Q_{track}}{\sum(\vec{p}_{track} \cdot \vec{p}_{jet})^{0.5}} \tag{1}$$

The value of 0.5 as the exponent of the weight has been optimized to give the best performance of the JetQ algorithm. If the JetQ value is positive we assign the b jet to a $\bar{b}$ quark and if the JetQ value is negative we assign the b jet to a b quark. With this algorithm we obtain a selection efficiency based on the MC of 98% and a purity of 61%.

A. Calibration of the JetQ purity in data

Since MC are not necessarily reliable in terms of jet fragmentation, we correct the purity for the JetQ algorithm obtained from the MC by using a dijet data sample enriched in heavy flavor. This data sample is collected with a central muon ($p_T > 8$ GeV/c) trigger. Events are then required to have a muon track with $p_T > 9$ GeV/c and be within a jet with $E_T > 20 GeV$ (this is the muon jet). There should be another jet back to back with the muon jet that has $E_T > 20$ GeV (this is the away jet). We require both jets to be identified as b jets using the secondary vertex algorithm. The JetQ purity can be obtained by counting the number of events where the charge of the muon is opposite to the JetQ value applied on the away jet over the total number of selected events. This observed purity should be corrected for a number of effects: if the muon came from a secondary decay its charge will be opposite than if it came directly from a b decay, if the B meson underwent mixing the charge of the muon will also flip sign and finally, if one of the 2 b jets was misidentified then there should be no correlation between the JetQ value and the charge of the identified muon. The first two effects can be obtained from MC. The last effect is calculated from the data itself.

In order to obtain the $b\bar{b}$ fraction (where both the muon jet and the away jet came from a b quark) we make use of 2 template fits. The first makes use of the distribution of p_{Trel} (transverse component of the muon with respect to the jet axis) which tends to peak at larger values when the muon is coming from a b jet than when it is coming from a c or light quark jet. The template shapes are very similar for the cases where the muon is coming from a c or light quark jet so we do a 2 template fit to get the fraction of times that the muon is coming from a b jet. Since this does not guarantee that the away jet is also coming from a b jet we need to combine this template fit result with another template fit. This time we make use of the secondary vertex mass distribution of the away jet, which shows that as the incoming quark mass is higher, the secondary vertex mass distribution tends to peak at higher values. In this case we perform a 3 template fits. Also, we notice that the template shapes are different according to the value of the away jet E_T. Since the MC might not be reliable in providing the E_T distribution of the template shapes in the case of light quarks (since this corresponds to light quarks misidentified as a b quark) we perform all template fits in 9 bins of away jet E_T. We obtain the $b\bar{b}$ fraction in each E_T bin by computing the average b fraction between its lowest and highest value. The highest value is the fraction coming from the secondary vertex mass template fit. The lowest value is obtained by subtracting from the highest value the non-b fraction coming from the p_{Trel} template fit. The uncertainty on the average value covers the difference with the highest and lowest value.

Combining the $b\bar{b}$ fraction with the secondary and mixing fractions we can obtain the real purity from the observed purity in each away jet E_T bin. We decide to compute a scale factor between the purity obtained in data and the purity obtained in MC. We see no dependence with away jet E_T of this scale factor. The systematics on the scale factor comes from varying the template shapes, varying the fraction of secondary and mixing, and also allowing some away jet E_T dependence. We obtain a value of $SF = 0.99 \pm 0.01(stat) \pm 0.03(syst)$.

V. BACKGROUNDS

The dominant background is QCD production of W plus multijet events. These events enter the signal sample when either one of the jets is a b jet, or a light quark jet is misidentified as a b jet. Other backgrounds include QCD multijet events where 2 jets are misidentified as b jets, single top production and diboson events. The amount of background is very low ($\approx 15\%$) because we are requesting at least 2 jets to be identified as b jets.

We obtain the background predictions with a method as the one used for the cross-section measurement [8] and top mass measurement [9] and compute the efficiency of the χ^2 cut and JetQ selection using MC samples for each background with the exception of the QCD fakes for which we used a data based method. Finally, we look at each background to see if there is a correlation between the charge of the signal lepton and the JetQ value of the corresponding b jet. We do not expect any correlation except for a few processes such as: single top quark events and QCD $b\bar{b}$ events that get selected because a semileptonic lepton was identified as a signal lepton. In the former case we used MC to estimate possible correlation, while for the latter case we run over the data sample where all the selection

Background	**Prediction**	**Pairing ϵ**	**JetQ ϵ**	**N_b or N_s (pairs)**
W+HF	66.3 ± 21.8	0.15 ± 0.004	0.97 ± 0.003	19.5 ± 6.4
QCD fakes	18.0 ± 13.5	0.17 ± 0.08	0.88 ± 0.12	5.4 ± 4.8
Diboson	4.7 ± 0.7	0.22 ± 0.02	0.97 ± 0.01	2.0 ± 0.4
Mistag	9.7 ± 2.6	0.15 ± 0.02	0.96 ± 0.02	2.8 ± 0.8
Singletop	10.6 ± 1.3	0.21 ± 0.004	0.97 ± 0.003	4.4 ± 0.5
Total	$\mathbf{109.2 \pm 25.9}$	**-**	**-**	$\mathbf{34.0 \pm 8.1}$

TABLE I: Background expectation based on the Pairing and JetQ efficiencies.

Background	**N_b**	**Purity**	**N^+**	**N^-**
W+HF	19.5 ± 6.4	0.5 ± 0.0	9.7 ± 3.2	9.7 ± 3.2
QCD fakes	5.4 ± 4.8	0.48 ± 0.06	2.6 ± 2.3	2.8 ± 2.5
Diboson	2.0 ± 0.4	0.5 ± 0.0	1.0 ± 0.2	1.0 ± 0.2
Mistag	2.8 ± 0.8	0.5 ± 0.0	1.4 ± 0.4	1.4 ± 0.4
Singletop	4.4 ± 0.5	0.51 ± 0.01	2.25 ± 0.3	2.15 ± 0.3
Total	$\mathbf{34.0 \pm 8.1}$	$\mathbf{0.50 \pm 0.01}$	$\mathbf{16.9 \pm 4.0}$	$\mathbf{17.0 \pm 4.1}$

TABLE II: Background purities (correlation) and expected number of SM like (N^+) or Exotic Model like (N^-) events.

cuts are applied except for those of the primary lepton which is now required to fail at least two identification criteria (fake lepton).

Table I summarizes the background predictions while table II summarizes the amount of correlation for each background.

VI. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties in this analysis come from MC modeling of the geometrical and kinematic acceptance, knowledge of the secondary vertex tagging efficiency, the effect on the acceptance of the uncertainty on the jet energy scale, uncertainties on the background predictions, and the uncertainty on the luminosity.

Monte Carlo modeling of geometrical and kinematic acceptance include effects of parton distribution functions (PDFs), initial and final state radiation (ISR and FSR), and jet energy scale. These are estimated by comparing different choices for PDFs and varying ISR, FSR and the jet energy scale in the Monte Carlo. An additional source comes from the choice of the generator, for which we compare `PYTHIA` with `HERWIG`.

All of these systematic uncertainties affect the predicted number of signal and background (for details see [8] and [9]) and also the efficiency and purity of the pairing and the efficiency and purity of the JetQ selection. There are additional systematic uncertainty which will affect the pairing efficiency: the effect of the top mass used for the MC and in the χ^2 constraint. To obtain a systematic uncertainty for the top mass, we have obtained the pairing efficiency/purity from different samples generated with different top mass. Finally, for the JetQ purity systematic uncertainty, we took the value obtained from the calibration in data and added in quadrature the effect of ISR and FSR, since may be those are different between a $b\bar{b}$ and a $t\bar{t}$ environment.

In table III we show the systematic uncertainties on the pairing efficiency and purity and on the JetQ selection efficiency and purity.

Systematics (in %)	pairing ϵ	JetQ ϵ	pairing purity	JetQ purity
Jet Energy Scale	0.2	0.04	0.1	0.1
ISR/FSR	0.5	0.1	0.2	0.2
MC generator	0.2	0.1	0.1	(0.7)
top mass	0.4	0.2	0.9	0.5
PDF	0.7	0.02	0.1	0.02
total	1.0	0.3	1.0	0.6

TABLE III: Summary of systematics uncertainties (in %).

	Prediction	**Pairing ϵ**	**JetQ ϵ**	**N_b or N_s (pairs)**
Total Background	$\mathbf{109.2 \pm 25.9}$	-	-	$\mathbf{34.0 \pm 8.1}$
Signal	$\mathbf{671.3 \pm 110.8}$	$\mathbf{0.532 \pm^{\pm 0.001(stat)}_{\pm 0.005(syst)}}$	$\mathbf{0.979 \pm^{\pm 0.000(stat)}_{\pm 0.002(syst)}}$	$\mathbf{699.6 \pm 115.7}$

TABLE IV: Background and signal expectation.

	N_b or N_s (pairs)	**Purity**	**N^+**	**N^-**
Tota Background	$\mathbf{34.0 \pm 8.1}$	$\mathbf{0.50 \pm 0.01}$	$\mathbf{16.9 \pm 4.0}$	$\mathbf{17.0 \pm 4.1}$
Signal	$\mathbf{699.6 \pm 115.7}$	$\mathbf{0.562^{\pm 0.004(stat)}_{\pm 0.011(syst)}}$	$\mathbf{393.5 \pm 65.6}$	$\mathbf{306.1 \pm 51.3}$

TABLE V: Background and signal purities (correlation) and expected number of SM like (N^+) or Exotic Model like (N^-) events.

VII. SIGNAL AND BACKGROUND ESTIMATES

In table IV we show the signal and background estimates while table V shows the signal and background purities. The combined efficiency is obtained by multiplying the pairing efficiency and the JetQ efficiency. The combined purity is more complicated since if the pairing is wrong and if the JetQ is also wrong, that still gives the same answer as having those right. Also, there is a small probability that the b jet are misidentified in which case they will random correlation with the lepton. In summary, we use the following equation to get the combined purity:

$$p = f_{nonb}SF_{nonb}p_{nonb} + (1 - f_{nonb}SF_{nonb})(p_{pairing}p_{JetQ}SF_{JetQ} + (1 - p_{pairing})(1 - p_{JetQ}SF_{JetQ})) \tag{2}$$

where f_{nonb} is the fraction of signal MC events where we have misidentified the b jet, SF_{nonb} is a scale factor between data and MC which takes into account the fact that the MC underestimates the number of misidentified b jets, p_{nonb} represents whether there is a correlation between the lepton and the jet that was misidentified as a b jet, $p_{pairing}$ is the pairing purity for cases where the JetQ was defined, p_{JetQ} is the JetQ purity for the cases where the pairing cut was applied and SF_{JetQ} is the scale factor between data and MC for the JetQ obtained from the data calibration study (see section IV A). In table VI we show the values used for this equation.

Table VII summarizes the important numbers from the analysis that will go into the statitstical treatment, described in the next section.

VIII. STATISTICAL TREATMENT

Once we apply our pairing and JetQ selection on the data we can label each data pair as being standard model like (SM-like) or exotic quark model like (XM-like). In order to obtain a confidence limit on either hypothesis we make use of the profile likelihood method described in [10]. The method is to write the likelihood as a function of f_+ (the fraction of signal SM pairs) and of the nuisance parameters (the number of signal and background, the purity of signal and background, see section VII). We then scan each value of f_+ between -1 and 2 and at each point minimize the likelihood over the nuisance parameters. In this way we can obtain a likelihood curve as a function of f_+ so that at the minimum of that curve is the maximum likelihood estimate (MLE), $\hat{f}_+$. The likelihood contains a Poisson term representative of the combined signal and background purity as well as Gaussian terms for each nuisance parameter and their total uncertainty. In Figure 1 we show the distributions of $\hat{f}_+$ under the SM and XM hypotheses. We

f_{nonb}	0.079 ± 0.001
SF_{nonb}	1.01 ± 0.03
p_{nonb}	0.5 ± 0.01
p_{pair}	$0.833 \pm 0.001(stat) \pm 0.008(syst)$
p_{JQ}	$0.608 \pm 0.001(stat) \pm 0.003(syst)$
SF_{JQ}	$0.99 \pm 0.01(stat) \pm 0.03(syst)$

TABLE VI: Elements needed to compute the combined purity, the description is in the text.

N_s	699.6 ± 115.7
N_b	34.0 ± 8.1
p_s	$0.562 \pm 0.004(stat) \pm 0.011(syst)$
p_b	0.50 ± 0.01

TABLE VII: Expected number of Background and Signal pairs together with the corresponding purities.

compute two p-values based on $\hat{f}_+$ as test statistic: p_{SM}, the lower tail area under the SM distribution, and p_{XM}, the upper tail area under the XM distribution. To reject the SM we require $p_{SM} \leq \alpha_{SM}$, where α_{SM} is the standard 5-sigma discovery threshold of 2.87×10^{-7}. To exclude the XM we similarly require $p_{XM} \leq \alpha_{XM}$. The choice of α_{XM} requires some care however, as it should reflect the high sensitivity of our measurement. When the SM is true, we need to balance our desire to exclude the XM at the highest possible confidence level against the risk of not excluding it due to lack of sensitivity. The XM exclusion confidence level is $1 - \alpha_{XM}$, and the probability of not excluding the XM when the SM is true is the Type-II error β_{XM} of the test. A plot of β_{XM} versus α_{XM} is shown in Fig. 2 : as expected, low α_{XM} can only be achieved at the price of high β_{XM}. One way to choose α_{XM} is to select the value for which $\alpha_{XM} = \beta_{XM}$. Although this procedure takes measurement sensitivity into account, in the sense of yielding a higher value of $1 - \alpha_{XM}$ as the sensitivity improves, the resulting confidence levels are not standard. Standard values of α_{XM} include 10%, 5%, 1%, 0.1%, etc. We therefore set α_{XM} to the lowest standard value that is still higher than the associated value of β_{XM}. Again looking at Fig. 2 , we find that the desired value of α_{XM} is 1%, and corresponds to $\beta_{XM} = 0.16\%$ (green triangle on the plot).

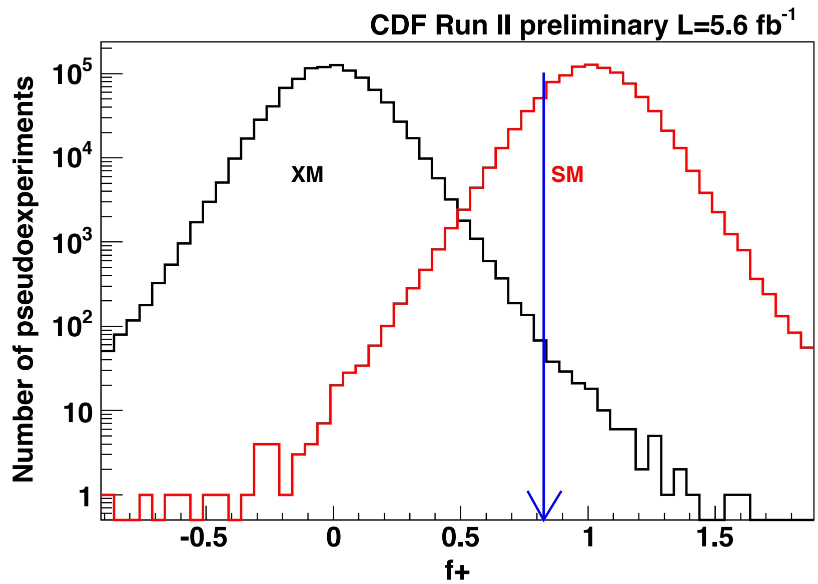

FIG. 1: Distribution of best f_+ from pseudo-experiments assuming the XM and the SM.

We have also chosen to compute a Bayes Factor which is the ratio of posterior odds to prior odds for the SM over the XM. To take into account the systematic uncertainties, we integrate the likelihood over the nuisance parameters separately for the numerator (SM) and the denominator (XM). By taking $2Ln(BF)$ we can interpret this value according to a well-established scale [11].

IX. RESULTS

In table VIII we show the number of events and pairs after applying the pairing and JetQ selection and also the number of pairs corresponding to the SM and XM hypothesis.

Using those numbers we get a log likelihood curve shown in figure 3. We see that the minimum of the curve is at a value of $f_+ = 0.83$.

This corresponds to a p-value under SM hypothesis $p_{SM} = 0.134$ and p-value under XM hypothesis $p_{XM} = 1.4x10^{-4}$

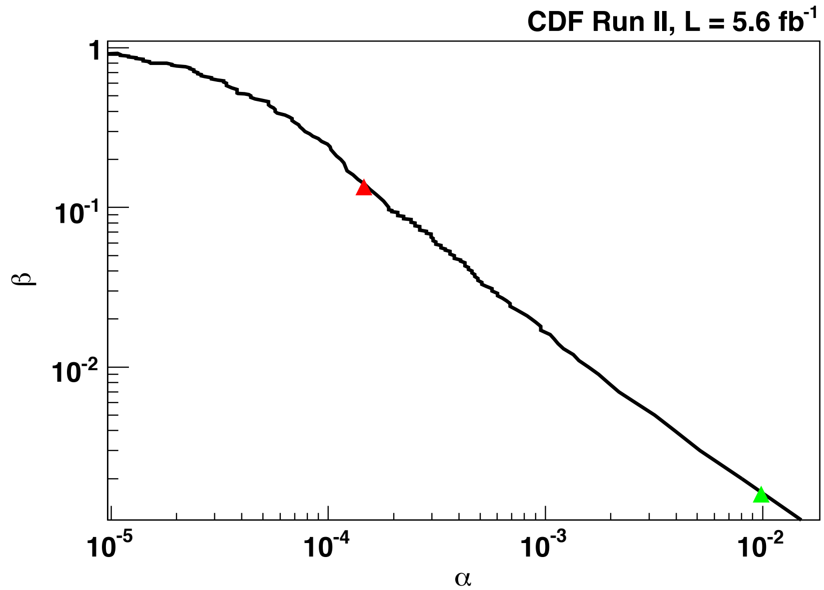

FIG. 2: Variation of β_{XM} (the probability of accepting a false XM) with α_{XM} (the probability of rejecting a true XM) for the CDF top charge measurement. The green triangle represents our a priori choice of $\alpha_{XM} = 1\%$, corresponding to $\beta_{XM} = 0.16\%$, while the red triangle represents the observed p-values and is plotted at the coordinates (p_{XM}, p_{SM}).

Observed	After Pairing	JQ defined	SM	XM
815	397	774 pairs	416	358

TABLE VIII: Observed number of events before and after the pairing cut. Observed number of pairs with the Jet Charge defined and observed SM like (SM) and Exotic Model like (XM) pairs.

(see figure 1). The p-value under SM hypothesis is greater than 0.13% so we do not exclude the SM hypothesis and because of the p-value under XM hypothesis is lower that 1% we exclude XM hypothesis with 99% confidence level. We obtain a value of $2Ln(BF) = 19.6$, and conclude that the data favors *very strongly* the SM over the XM hypothesis. In figure 4 we show the graphical representation of our results.

X. CROSS-CHECK ON LEPTON TYPE

We checked the results for electrons and muons separately. Summary of the expected number of Signal or Background pairs as well as corresponding purities can be found in the table IX. In figures 5, 6 we show the distribution of the best f_+ obtained using pseudo-experiments based on either the SM hypothesis or the XM hypothesis for electrons and muons separately.

	electrons	muons
N_s	307.8 ± 50.8	391.7 ± 66.6
N_b	17.2 ± 4.6	16.8 ± 4.0
p_s	0.56 ± 0.01	0.56 ± 0.01
p_b	0.50 ± 0.02	0.50 ± 0.01

TABLE IX: Expected number of Background and Signal pairs together with the corresponding purities for electrons and muons separately.

Because using only the electron or muon channels reduces the statistics of the sample and therefore the sensitivity of the analysis, the a-priori criteria for the XM (following the procedure mentioned above), for each channel, corresponds to $\alpha_{XM} = 5\%$.

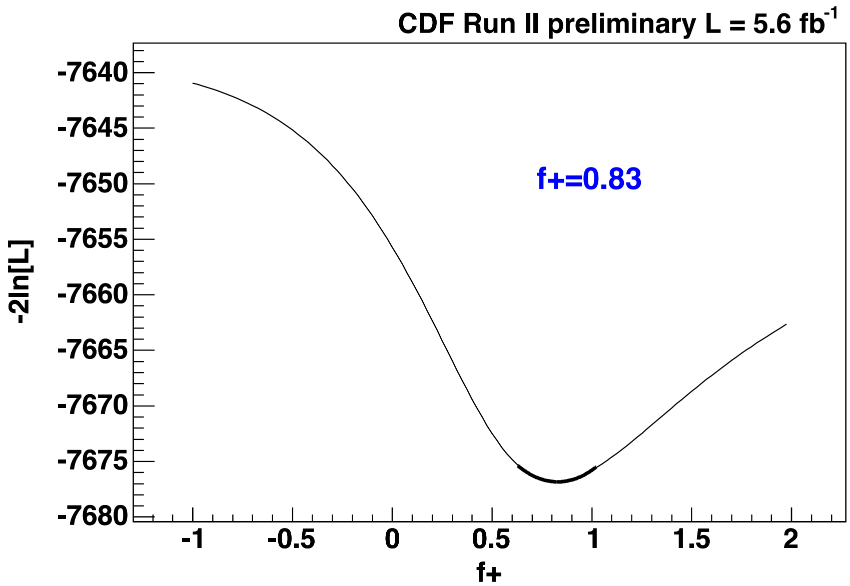

FIG. 3: -2LnL curve corresponding to the results obtained, the minimum is at a value of $f_+ = 0.83$.

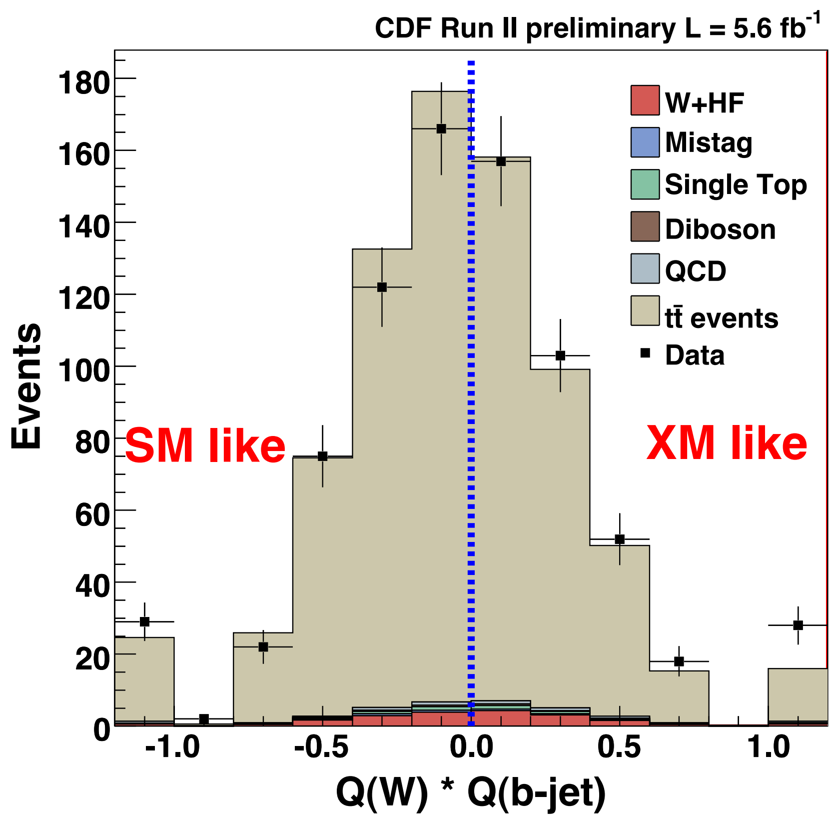

FIG. 4: W charge * JetQ for the LJ and DIL channel combined, SM-like pairs are on the negative side of the plot while XM-like pairs are on the positive side.

As we can see in the table X the p-value under the SM hypothesis for electrons is 0.671 and for muons 0.026. Both values are higher than the a-priori criteria value 0.0013, what means that we do not exclude SM in either electrons or muons case. Both p-values under the XM hypothesis are lower than 5%, what means that we can exclude the XM hypothesis with 95% CL.
Based on Bayes Factor values electrons favors *very strongly* the SM over the XM hypothesis, while muons favors *positively* the SM over the XM hypothesis.

	electrons	muons
pairs	206 SM like / 155 XM like	210 SM like / 203 XM like
$f+$	1.11	0.57
p_{SM}	0.671	0.026
p_{XM}	0.0004	0.007
$2ln(BF)$	20.3	2.7

TABLE X: Results of statistical treatment for electrons and muons separately.

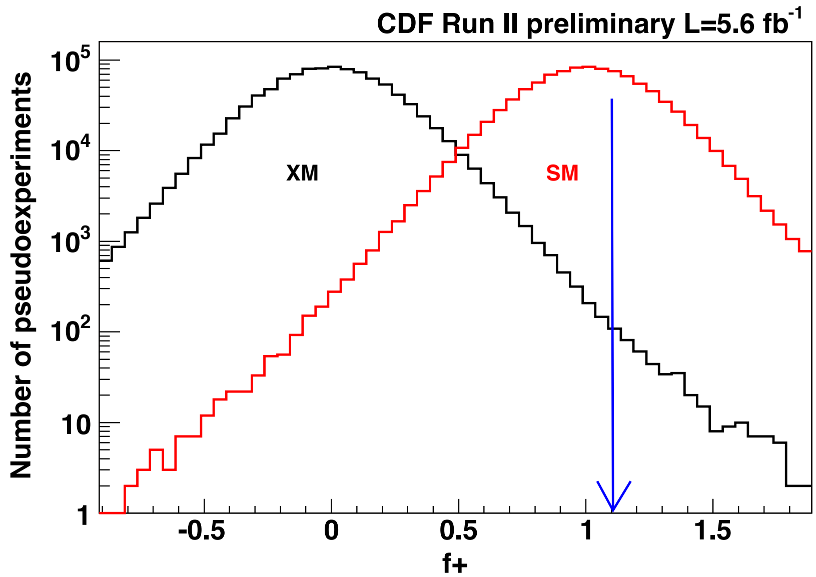

FIG. 5: Distribution of best f_+ from pseudo-experiments assuming the XM and the SM for electrons.

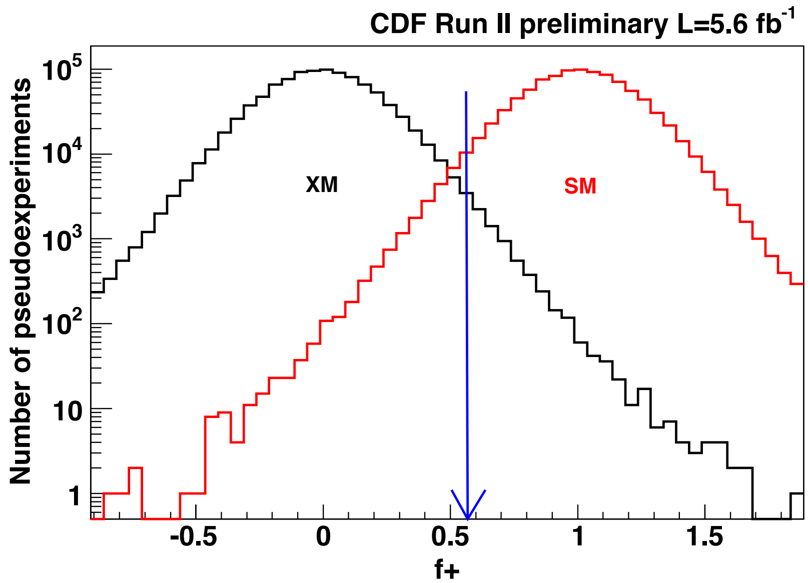

FIG. 6: Distribution of best f_+ from pseudo-experiments assuming the XM and the SM for muons.

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