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First CDF Measurement of the Top Quark Charge using the Top Decay Products

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 close to 1fb^{-1} of data and defining the probability of incorrectly rejecting the SM to be 1%, we found the result to be consistent with the standard model, while excluding an exotic quark hypothesis with 81% confidence.

Preliminary Results for Winter 2007 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). As yet undone is measuring the top quark charge. The D0 collaboration already has a measurement of this property based on 370 pb^{-1} of data [1]. 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 [2] 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.

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 [3].

II. DATA SAMPLE & EVENT SELECTION

This analysis is based on an integrated luminosity of close to 1fb^{-1} collected with the CDFII detector between March 2002 and February 2006. 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 $E_T(ME_T)$ >20 GeV and at least 3 jets with E_T >15 GeV in addition to a fourth jet with $E_T > 8$ GeV.

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 48% while the efficiency of misidentifying a light quark is about 1%.

From the inclusive lepton dataset we also select events corresponding to the "dilepton" (DIL) channel: we select events offline with at least 2 reconstructed isolated electron E_T (muon P_T) greater than 20 GeV and with opposite sign, missing E_T >25 GeV and away from any jet, at least 2 jets with E_T >15 GeV and we also require that the total transverse energy in the event: $H_T = p_{Tlep} + E_{Tjets} + ME_T$ be greater than 200 GeV. Similarly to the LJ channel, we require that the event has at least 1 jet identified as a b jet using the secondary vertex algorithm. In the case of the DIL channel, the secondary vertex algorithm is tuned such that the efficiency of identifying a b jet is about 40% while the efficiency of misidentifying a light quark is about 0.5%. The $t\bar{t}$ Monte Carlo (MC) uses PYTHIA as the generator.

III. PAIRING BETWEEN THE W AND THE b JET

In the LJ channel, 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 175 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 56% and a purity of 84%.

In the DIL channel, we assign the highest 2 E_T jets as the b jets. In order to pair each lepton with the right b jet we make use of the variable: $M_{lb}^2 = ((E_l + E_b)^2 - (\vec{p_l} + \vec{p_b})^2)$. We order the 4 values of M_{lb}^2 in each event. We pick as the right combination the one which does not produce the largest value of M_{lb}^2. To increase further the purity (ratio of correct combinations over the total number of events), we only select events for which the maximum value of M_{lb}^2 is greater than 22,000 GeV^2/c^4. In doing so, we obtain a selection efficiency based on the MC of 37% and a pairing purity of 96%.

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% (87%) for the LJ (DIL) channel 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 obtained from requiring a central muon with $p_T > 8$ GeV/c to trigger. Events are then required to have a muon track with $p_T > 8$ GeV/c and be within a jet with $E_T > 9GeV$ (this is the muon jet). There should be another jet back to back with the muon jet that has $E_T > 15$ 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, which is the dominant uncertainty. We obtain a value of $SF = 1.03 \pm 0.02 \pm 0.04$.

V. BACKGROUNDS

In the LJ channel, 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

Background	Prediction	Efficiency	N_b
LJ (695 pb^{-1})			
W+HF	5.29 ± 1.15	0.15 ± 0.01	0.77 ± 0.17
QCD fakes	1.81 ± 0.95	0.20 ± 0.10	0.36 ± 0.27
Diboson	0.38 ± 0.00	0.10 ± 0.05	0.04 ± 0.02
Mistag	1.32 ± 1.19	0.08 ± 0.03	0.11 ± 0.11
Singletop	0.77 ± 0.06	0.16 ± 0.01	0.13 ± 0.01
Total	9.57 ± 1.91	-	1.40 ± 0.34
DIL (955 pb^{-1})			
Drell-Yan	$0.38^{+0.76}_{-0.38}$	-	$0 + 0.38$
Fakes	$0.81^{+1.62}_{-0.81}$	-	$0 + 0.81$
Diboson	0.0 ± 0.1	-	$0 + 0.1$
Total	$1.19^{+1.79}_{-0.9}$	-	$0 + 0.9$
Total Background			$1.40^{+0.96}_{-0.34}$

TABLE I: Background expectation for LJ and DIL channels.

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 (15%) because we are requesting at least 2 jets to be identified as b jets. In the DIL channel, the dominant background is coming from QCD production of W plus multijet events where one jet was misidentified as a lepton and one jet was misidentified as a b jet. The other background is Drell-Yan plus multijet production where we have instrumental ME_T and a jet misidentified as a b jet. Similarly to the LJ channel the background fraction is very low (4%) because of the requirement of having at least 1 jet identified as a b jet.

We make use of the background predictions coming from the cross-section measurements [4] and [5] and compute the efficiency of the χ^2 cut (LJ) or M^2_{lbmax} cut (DIL) and JetQ selection using MC samples for each background. 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 in the LJ channel: if a QCD $b\bar{b}$ event gets selected because a semileptonic lepton was identified as a signal lepton, then we expect some correlation between the JetQ value of the identified b jet and this lepton. In order to get an upper limit on this correlation we make use of the data sample where all the LJ selection cuts are applied except that we require low $ME_T < 15$ GeV and for the lepton to be non-isolated. This region is dominated by QCD background events. In that subsample of data events we require the identified electron to be back to back with a jet identified as a b jet. We check the correlation between the charge of the electron and the JetQ value on the back to back jet. We measure a correlation of $0.545^{+0.005}_{-0.045}$ where the asymmetric uncertainty ensures that the lower value of the correlation is 0.5 corresponding to no correlation. We also expect some correlation in the case of single top events, which we estimate using MC events.

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 [4] and [5]) and also the efficiency and purity of the pairing and the efficiency and purity of the JetQ selection. There are additional systematic uncertainties which will affect the pairing efficiency: the effect of the top mass used for the MC and in the χ^2 constraint for the LJ channel and also any assumption about W helicity in the case of the M^2_{lbmax} cut. To obtain a systematic uncertainty for the top mass, we have obtained the pairing efficiency from different samples generated with different top mass. As for the W helicity, we have reweighted events at the generator level according

Background	N_b	**Purity**	N^+	N^-
LJ (695 pb^{-1})				
W+HF	0.77 ± 0.17	0.5 ± 0.0	0.38 ± 0.09	0.38 ± 0.09
QCD fakes	0.36 ± 0.27	$0.545^{+0.005}_{-0.04}$	0.20 ± 0.15	0.16 ± 0.12
Diboson	0.04 ± 0.02	0.5 ± 0.0	0.02 ± 0.01	0.02 ± 0.01
Mistag	0.11 ± 0.11	0.5 ± 0.0	0.05 ± 0.05	0.05 ± 0.05
Singletop	0.13 ± 0.01	0.58 ± 0.02	0.07 ± 0.01	0.05 ± 0.01
Total	1.40 ± 0.34	$0.518^{+0.006}_{-0.012}$	0.73 ± 0.18	0.67 ± 0.16
DIL (955 pb^{-1})				
Drell-Yan	$0 + 0.38$	0.5 ± 0.0	$0 + 0.38$	$0 + 0.38$
Fakes	$0 + 0.81$	0.5 ± 0.0	$0 + 0.81$	$0 + 0.81$
Diboson	$0 + 0.1$	0.5 ± 0.0	$0 + 0.1$	$0 + 0.1$
Total	$0 + 0.9$	-	$0 + 0.9$	$0 + 0.9$
Total Background	$1.40^{+0.96}_{-0.34}$	$0.518^{+0.006}_{-0.012}$	$0.73^{+0.92}_{-0.18}$	$0.67^{+0.91}_{-0.16}$

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

Systematics (in %)	pairing eff	pairing purity	JetQ eff	JetQ purity
LJ				
ISR/FSR	2.3	1.2	0	1.4
MC generator	0.8	0.3	0	(2.0)
JES	3.1	1.0	0	0
PDF	1.1	0.3	0	0
top mass	1.0	2.4	0	0
total	4.2	2.9	0	1.4
DIL				
ISR/FSR	4.6	1.0	1.2	1.9
MC generator	0	0	1.0	(2.0)
JES	4.2	0.8	0.4	0
PDF	4.1	0.3	0	0
top mass	7	2	0 0	0
W polarization	1.5	0	0	0
total	10.3	2.4	1.6	1.9

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

to their $cos\theta^*$ value (in the W rest frame the angle between the lepton and the top quark) in such a way as to be representative of events with different values of W helicity within the range of the latest W helicity measurements [6]. Finally, as 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.

VII. SIGNAL AND BACKGROUND ESTIMATES

In table V we show the signal and background estimates while table VI 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:

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

	DIL	LJ
f_{nonb}	0.075 ± 0.001	0.055 ± 0.001
SF_{nonb}	1.05 ± 0.05	1.05 ± 0.05
p_{nonb}	0.5 ± 0.01	0.5 ± 0.01
p_{pair}	$0.959 \pm 0.003(stat) \pm 0.013(sys)$	$0.844 \pm 0.003(stat) \pm 0.024(sys)$
p_{JQ}	$0.603 \pm 0.005(stat) \pm 0.011(sys)$	$0.608 \pm 0.003(stat) \pm 0.009(sys)$
SF_{JQ}	$1.03 \pm 0.02(stat) \pm 0.04(sys)$	$1.03 \pm 0.02(stat) \pm 0.04(sys)$

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

	Prediction	**Efficiency**	N_b **or** N_s
LJ (695 pb^{-1})			
Total LJ Background	9.57 ± 1.91	-	1.40 ± 0.34
Signal	$64.86^{\pm 0.64(stat)}_{\pm 14.27(sys)}$	$0.545^{\pm 0.002(stat)}_{\pm 0.023(sys)}$	$35.35^{\pm 0.37(stat)}_{\pm 7.92(sys)}$
DIL (955 pb^{-1})			
Total DIL Background	$1.19^{+1.79}_{-0.9}$	-	$0 + 0.9$
Signal	$32.4^{\pm 1.3(stat)}_{\pm 4.0(sys)}$	$0.318^{\pm 0.004(stat)}_{\pm 0.033(sys)}$	$10.30^{\pm 0.43(stat)}_{\pm 1.66(sys)}$
Total Background			$1.40^{+0.96}_{-0.34}$
Total Signal			$45.65^{\pm 0.57(stat)}_{\pm 8.09(sys)}$

TABLE V: Background and signal expectation for LJ and DIL channels.

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 IV we show the values used for this equation for the LJ and DIL channels.

Finally, since each event contains 2 pairs of top quarks (or exotic quarks), we can multiply by 2 the signal and background estimates. Those final estimates are shown in table VII.

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

	N_b **or** N_s	**Purity**	N^+	N^-
LJ (695 pb^{-1})				
Total LJ background	1.40 ± 0.34	$0.518^{+0.006}_{-0.012}$	0.73 ± 0.18	0.67 ± 0.16
Signal	$35.35^{\pm 0.37(stat)}_{\pm 7.92(sys)}$	$0.582^{\pm 0.008(stat)}_{\pm 0.018(sys)}$	$20.57^{\pm 0.36(stat)}_{\pm 4.65(sys)}$	$14.78^{\pm 0.33(stat)}_{\pm 3.37(sys)}$
DIL (955 pb^{-1})				
Total DIL background	$0 + 0.9$	-	$0 + 0.9$	$0 + 0.9$
Signal	$10.30^{\pm 0.43(stat)}_{\pm 1.66(sys)}$	$0.602^{\pm 0.011(stat)}_{\pm 0.023(sys)}$	$6.20^{\pm 0.28(stat)}_{\pm 1.03(sys)}$	$4.10^{\pm 0.21(stat)}_{\pm 0.70(sys)}$
Total Background	$1.40^{+0.96}_{-0.34}$	$0.518^{+0.006}_{-0.012}$	$0.73^{+0.92}_{-0.18}$	$0.67^{+0.91}_{-0.16}$
Total Signal	$45.65^{\pm 0.57(stat)}_{\pm 8.09(sys)}$	$0.586^{\pm 0.007(stat)}_{\pm 0.015(sys)}$	$26.77^{\pm 0.46(stat)}_{\pm 4.76(sys)}$	$18.87^{\pm 0.39(stat)}_{\pm 3.44(sys)}$

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

N_s	$91.30 \pm 1.14(stat) \pm 16.18(sys)$
N_b	2.80 ± 1.92
p_s	$0.586 \pm 0.007(stat) \pm 0.015(sys)$
p_b	0.518 ± 0.012

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

make use of the profile likelihood method described in [7]. 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 0 and 1 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 preferred value of 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 distribution of best f_+ obtained using pseudo-experiments based on either the SM hypothesis or the XM hypothesis. Using the SM as the null hypothesis, we show in figure 2 the distribution of p-values under the SM hypothesis if the XM hypothesis is true. We choose an a-priori value of α=1% which is the probability of incorrectly rejecting the SM hypothesis and obtain that 81% of p-values fall below this value of α.

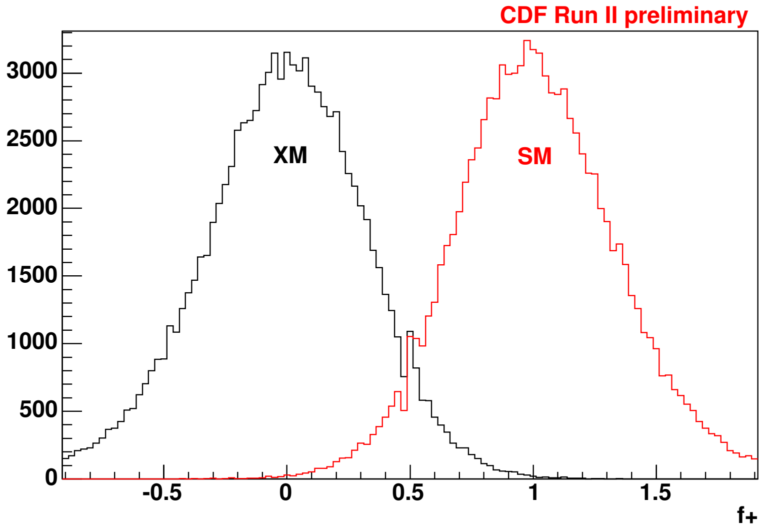

FIG. 1: Distribution of best f_+ from pseudo-experiments assuming the XM and the SM.

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 [8].

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 $f_+ = 0.88$. This corresponds to a p-value of 0.35 under the SM hypothesis. This value is greater than 1% so we conclude that we exclude the XM hypothesis with 81% confidence. We obtain a value of $2Ln(BF) = 8.5$ so we conclude that the data favors strongly the SM over the XM hypothesis. In figures 4 and 5 we show the graphical representation of our results. In summary our results suggest that the selected Wb events are from a standard model top quark instead of an exotic quark.

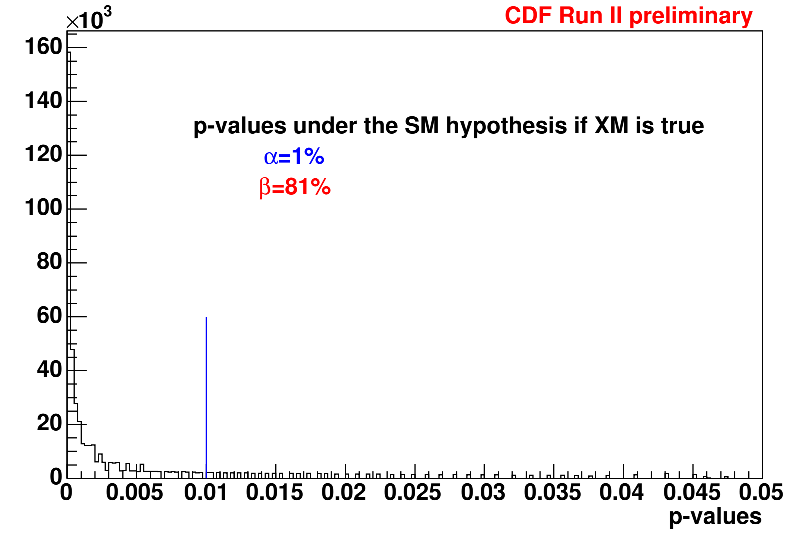

FIG. 2: Distribution of p-values under the SM hypothesis if the XM is true. α is the a-priori value chosen corresponding to the probability of incorrectly rejecting the SM hypothesis while β is the area under this curve below this value of α.

Yield	Observed	After Pairing	JQ defined	SM	XM
L + J	91	48	94 pairs	53	41
Dilepton	31	10	16 pairs	9	7
Total	122	58	110 pairs	62	48

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.

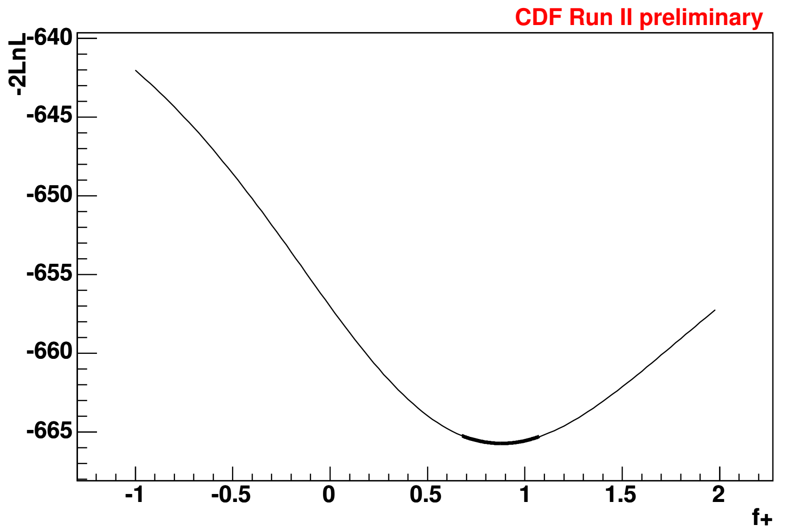

FIG. 3: -2LnL curve corresponding to the results obtained, the minimum is at a value of $f_{+} = 0.88$.

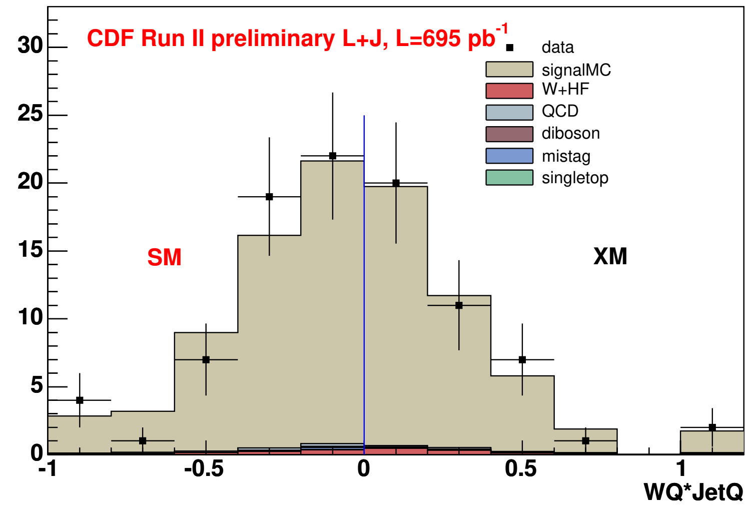

FIG. 4: W charge * JetQ for the LJ channel, SM-like pairs are on the negative side of the plot while XM-like pairs are on the positive side.

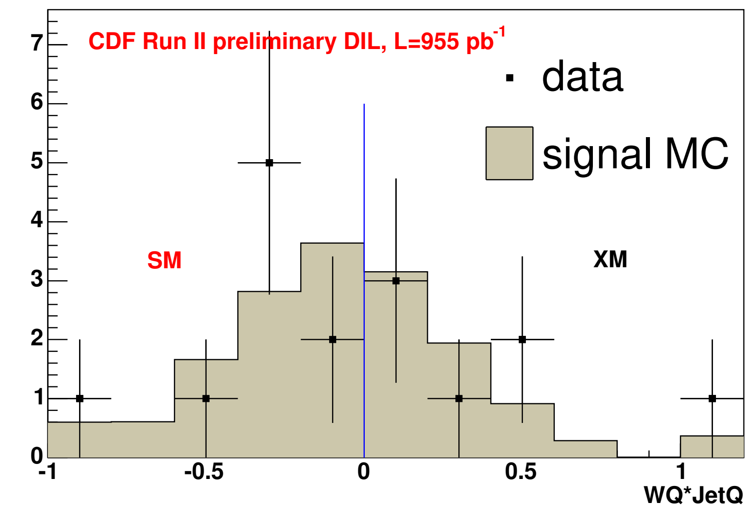

FIG. 5: W charge * JetQ for the DIL channel, SM-like pairs are on the negative side of the plot while XM-like pairs are on the positive side.

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