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# A measurement of the V+A fraction of $W$-bosons from top quark decay


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We search for possible effects from physics beyond the standard model in the decay of the top quark using a data sample enriched in $t\bar{t}$ produced in p$\bar{\text{p}}$ collisions at $\sqrt{s}$=1.96 TeV and collected by the CDF II experiment with an integrated luminosity of approximately 695 pb$^{-1}$ in the lepton+jets channel and 750 pb$^{-1}$ in the dilepton channel.

Neglecting the $b$-quark mass, the V-A charged weak current interaction forces the top (anti-top) quark to decay into $W^+$ ($W^-$) bosons with longitudinal and left-(right-) handed helicity. Effects from new massive particles or non-standard model couplings in the $t$-$W$-$b$ vertex may create $W^+$ ($W^-$) bosons with right-(left-) handed helicity which is an apparent V+A weak current. For subsequent $W$ boson decays to an $\ell\nu$ final state, the invariant mass squared of the lepton and the $b$-jet from top quark decay is an estimator of the $W$ boson helicity. The V+A fraction, $f_{V+A}$, of $W$ bosons from top quark decay under the assumption that the top quark mass is 175 GeV/$c^2$ is measured to be:

$$f_{V+A} = -0.06 \pm 0.25$$

In the absence of a signal, an upper limit is set on the V+A fraction of $W$ bosons from top quark decay with value:

$$f_{V+A} < 0.29 \text{ at } 95\% \text{ C.L.}$$

In terms of the fraction $f^+$ of right-handed $W^+$ bosons (left-handed $W^-$ bosons), we translate our $f_{V+A}$ result into $f^+$ by remembering that $f_{V+A} = f^+/0.3$ (if indeed $f^0 = 0.7$). We obtain:

$$f^+ = -0.02 \pm 0.07 \text{ and } f^+ < 0.09 \text{ at } 95\% \text{ CL.}$$


*Preliminary Results for Summer 2006 Conferences*

## I. INTRODUCTION AND MOTIVATION

The top quark, due to its high mass $m_t$~175 GeV/c$^2$, has a very short decay time, $\hbar/\Gamma$ with $\Gamma \sim G \cdot m_t^3 \simeq 1.4$ GeV, in comparison with the typical time-scale of hadronic interactions, of order $\hbar/\Lambda$ with $\Lambda \simeq 0.2$ GeV. Therefore, the top quark decays before hadronizing and its spin information is directly transferred to the decay products. The top quark decays with an almost 100% branching ratio via the weak decay $t \to bW^+$. In the SM, neglecting the $b$-quark mass, the V-A structure of this weak interaction predicts a fraction $f_0$ of $W^+$ bosons with longitudinal polarization at leading-order: $f_0 = m_t^2/(m_W^2 + m_t^2) = 0.70$ for $M_W = 80.4$ GeV/$c^2$ and $m_t = 175$ GeV/$c^2$. The left handed fraction of $W^+$ bosons is $f_- = 0.30$ and the right handed is $f_+ = 0.00$ [1].

However, theoretical models exist including a non-zero admixture of V+A weak current that could modify the predicted polarization of the top quark decay products [2], for instance non-zero values of $f_+$, indicating new physics. In this note, we investigate the possibility of new (axial) vector like couplings in the $t$-$W$-$b$ vertex. We do not consider other new couplings, such as those due to magnetic moment interactions. The fraction $f_0 = 0.7$ is therefore fixed. Also, a non-zero right handed coupling would not modify its value by any significant amount for our current experimental reach. We will quote our result in terms of the V+A fraction $f_{V+A}$ of $W$-bosons, which equals $f^+/0.30$ when $f_0 = 0.70$.

The analysis presented in this conference note uses the discriminating power between V+A and V-A in $t\bar{t}$ production and decay that is provided by $M^2_{\ell b}$, the invariant mass of the charged lepton and the $b$-quark in the decay chain $t \to bW$ followed by $W$ boson decay to leptons, $W \to \ell\nu$. The quantity $M^2_{\ell b}$ is related to the polar angle, $\psi^*$, of the charged lepton in the rest frame of the $W$ boson (the z-axis is defined to be the direction of motion of the $W$ boson in the rest frame of the top quark) through the relation:

$$M^2_{\ell b} = \frac{1}{2}(m_t^2 - m_W^2)(1 + \cos\psi^*) \tag{1}$$

that is exact in the limit $m_b \to 0$. The fraction $f_{V+A}$ of non-standard right-(left-) handed $W^+(W^-)$ bosons from top quark decay is measured by comparing the $M^2_{\ell b}$ distribution in data with Monte Carlo $M^2_{\ell b}$ templates built for backgrounds and $t\bar{t}$ with two assumptions: $f_{V+A} = 0$ and 1.

We make use of three independent samples collected by the CDF II detector [3]: a sample enriched in $t\bar{t}$ events where only one $W$ decays leptonically "*lepton plus jets*" (see section III) and a sample enriched in $t\bar{t}$ events where both $W$ bosons decay leptonically "*dileptons*"(see section IV). The lepton plus jets sample is sub-divided into a "*single b-tagged*" and a "*double b-tagged*" depending on the number of jets originated by the $b$-quark fragmentation as identified by the $b$-tagging algorithm. A binned likelihood fit technique is applied to obtain the best fitted value of $f_{V+A}$ in data: see section V for a detailed description of the technique and sensitivity studies. The systematic uncertainties are described in section VI and the results are discussed in section VII. A previous measurement based on CDF Run 1 data exploiting this technique has been reported in Ref. [4]. Other previously reported limits can be found in Refs. [5–8].

## II. DATA SAMPLES.

The analysis is based on a dataset collected by the CDF detector between March 2002 and September 2005. 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). Different offline criteria are applied to select $t\bar{t}$ dilepton and $t\bar{t}$ lepton plus jets events respectively (see the next sections III and IV). The integrated luminosity in the dilepton sample is 750$\pm$43 pb$^{-1}$. In the lepton plus jets sample, good quality data from the precision charged particle silicon detector is also required to ensure a proper performance of the $b$-tagging algorithm, resulting in a slightly lower integrated luminosity of 695$\pm$40 pb$^{-1}$.

## III. THE LEPTON PLUS JETS CHANNEL

The lepton plus jets channel aims at reconstructing $t\bar{t} \to W^+ b W^- \bar{b}$ where one of the $W$ bosons decays hadronically, $W \to q\bar{q}'$, and the other leptonically, $W \to \ell\nu$ with $\ell$ being an electron or muon. A detailed description of the selection can be found in [9]. The selection requires exactly one isolated, identified electron or muon with $E_T > 20$ GeV; missing transverse energy above 20 GeV; at least three jets with $E_T >$15 GeV after corrections for detector calibration and multiple interactions; and at least one of the jets identified as a $b$-jet by a displaced secondary vertex algorithm [10].

The main background consists of $W$ boson production with associated heavy flavor jets ($Wb\bar{b}$+1p, $Wc\bar{c}$+1p,$Wc$+2p where $p$ can be $u, d, s, g$) and mis-tags in $W$ boson production with non-heavy flavor jets. Both are modeled with

$Wb\bar{b}$+1p background events generated with Alpgen [11]+Herwig [12]. The remaining background consists of QCD events with jets misidentified as leptons, which is modeled from a control data sample.

### A. Signal acceptances, and effective cross sections for backgrounds.

The acceptance for the lepton plus jets is 3.36%±0.44% for single $b$-tagged events, and 1.17%±0.20% for double $b$-tagged events. These estimates are based on a PYTHIA MC sample with top quark mass of 175 GeV/$c^2$ and have been corrected for trigger efficiency and minor Monte Carlo/data discrepancies in lepton identification efficiencies. The signal $t\bar{t}$ Monte Carlo samples for V+A and V-A have been generated with high statistics using the MC generator Alpgen [11] for the hard process in combination with Pythia [13] for hadronization. These Alpgen samples are used to calculate the ratio $R(V-A/V+A)$ between the acceptance of V-A and V+A. For single and double $b$-tagged events we find $R(V-A/V+A) = 0.922 \pm 0.021$ and $R(V-A/V+A) = 0.926 \pm 0.010$ respectively. The V+A samples have a slightly higher acceptance due to the larger average transverse momentum of the charged lepton. The expected background rate is translated into an effective background cross section. The total effective cross section for all backgrounds together is $0.160 \pm 0.017$ pb for single $b$-tagged events, and $0.013 \pm 0.002$ pb for double $b$-tagged events.

### B. The $M^2_{\ell b}$ observable, signal and background templates.

In the case of single $b$-tagged events, the $M^2_{\ell b}$ observable is reconstructed by the invariant mass of the charged lepton and the $b$-tagged jet. This $M^2_{\ell b}$ distribution of single $b$-tagged events can be represented by a 1-D histogram, see Figure 1. Note that events with $M^2_{\ell b}$ above the upper edge of the highest bin in $M^2_{\ell b}$, that is the overflow events, are included in that bin. For V+A and V-A $t\bar{t}$, the high statistics Alpgen + Pythia samples are used to model the $M^2_{\ell b}$ distribution. The $W$+jets background $M^2_{\ell b}$ distribution is based on $Wb\bar{b}$+1p background, generated with Alpgen. The QCD background $M^2_{\ell b}$ distribution is obtained by using data events but requiring non-isolated leptons rather than isolated leptons. These two background types are then combined in the appropriate proportion (85% $W$+jets and 15% QCD) to form a total background distribution.

In the case of double $b$-tagged events, the distribution of the two $M^2_{\ell b}$ values for the invariant mass of the charged lepton and the two $b$-tagged jets can be represented by a 2-D histogram, see Figure 1. The x-ordinate is the invariant mass of the charged lepton and the highest $E_T$ $b$-tagged jet, the y-ordinate is the invariant mass of the charged lepton and the second highest $E_T$ $b$-tagged jet. Note that events with $M^2_{\ell b}$ above the upper edge of the highest bin in $M^2_{\ell b}$, that is the overflow events, are included in that bin. The binning of the 2-D $M^2_{\ell b}$ distributions is non-equidistant and has been optimized with the criterion of a minimum statistical significance of ≈20% in all the bins of the most statistically-limited background template. Note that the $W$+jets background distribution is based only on $Wb\bar{b}$+1p background, generated with Alpgen+Herwig. The amount of QCD background is small and therefore neglected.

## IV. THE DILEPTON CHANNEL

The event selection in the dilepton channel aims at reconstructing $t\bar{t} \rightarrow W^+bW^-\bar{b}$ events where both $W$ bosons decay leptonically, $W \rightarrow \ell\nu$, with $\ell$ being an electron or muon. A detailed description of the selection can be found in [14]. The selection requires two identified leptons (electrons or muons) with $E_T$ >20 GeV and of opposite charge, $\not{E}_T > 25$ GeV, at least two tight jets with $E_T > 15$ GeV, $H_T$ [18] $> 200$ GeV. For $ee$ and $\mu\mu$ events in the dilepton invariant mass window 76 < $M_{\ell\ell}$ < 106 GeV/$c^2$, we veto events with JetSig [19] > 8 $\sqrt{\text{GeV}}$.

Even with the invariant mass requirement above, the dominant background that mimics the top dilepton signature is Drell-Yan ($Z^*/\gamma \rightarrow e^+e^-, \mu^+\mu^-$) with associated jets from QCD initial state radiation, where the missing transverse energy comes from mis-measurements. The second important background results from processes with one lepton and a jet or a charged particle that has fluctuated to pass the lepton identification requirements - these are called fake-able events and are mainly from $W$ boson production with associated jets. Remaining backgrounds are massive diboson pair production, $WW$ and $WZ$, and $Z \rightarrow \tau^+\tau^-$ with jets from QCD initial state radiation.

### A. Signal acceptances and effective cross sections for backgrounds.

The acceptance for dileptons is 0.717%±0.007%. These estimates are based on a PYTHIA MC sample with top quark mass of 175 GeV/$c^2$ and have been corrected for trigger efficiency and minor Monte Carlo/data discrepancies

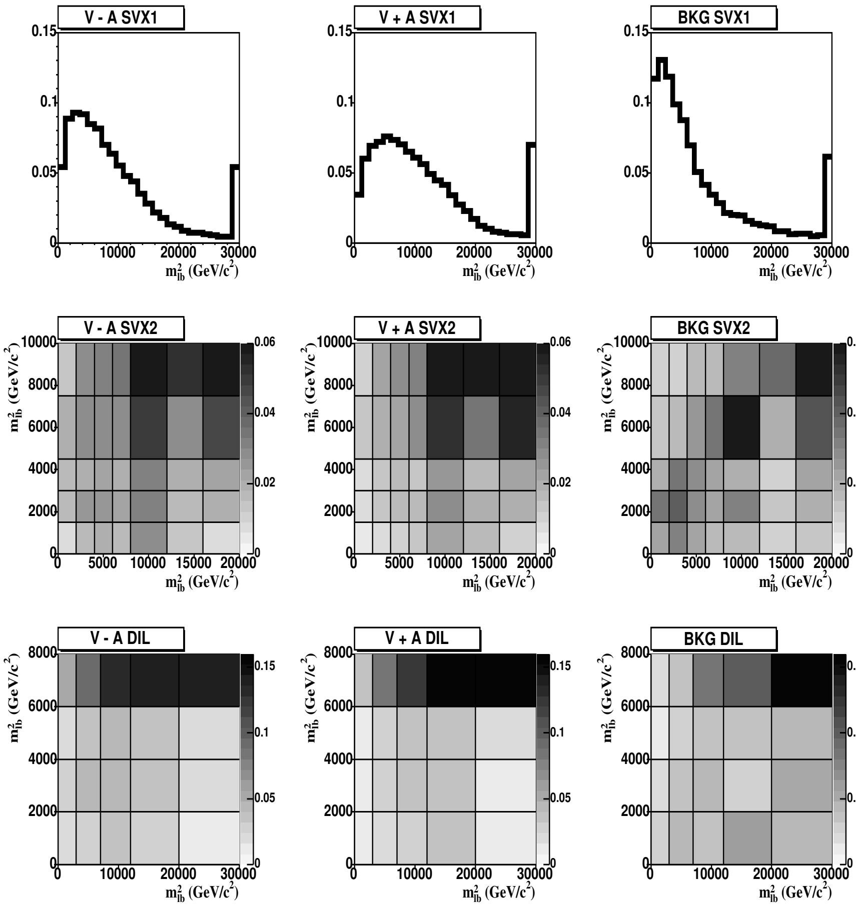


FIG. 1: The $M_{\ell b}^2$ template distributions for SVX1, SVX2 and dilepton events.

in lepton identification efficiencies. The Alpgen + Pythia samples are used to compute the relative ratio between the V-A and V+A acceptance, which is $R(V-A/V+A) = 0.879 \pm 0.014$.

The relative background composition and total background rates have been evaluated, see Ref. [14]. After properly normalizing to the combined luminosity for the dilepton sample, we obtain a total effective cross section for dilepton background of 0.026±0.006 pb.

### B. The $M_{\ell b}^2$ observable, signal and background templates.

No $b$-tagging information is required to reconstruct the $M_{\ell b}^2$ observable in the dilepton channel. Instead the two highest $E_T$ jets are assumed to be produced by the fragmentation of the $b$-quarks from decays of the top quarks. From MC studies at generator level, it was found that only about 20% of the top dilepton events after event selection have one of the two highest $E_T$ jets originated by another source than the $b$-quarks from top quark decay, that is ISR/FSR. The distribution of the two $M_{\ell b}^2$ values for the invariant mass of each charged lepton and the two jets can be represented by a 2-D histogram, see Figure 1. The x-ordinate is the invariant mass of a charged lepton and the highest $E_T$ jet, the y-ordinate is the invariant mass of the same charged lepton and the second highest $E_T$ jet. Each lepton in the dilepton event is paired with both high $E_T$ jets, yielding 2 entries per event when building the 2-D $M_{\ell b}^2$ distribution. Note that events with $M_{\ell b}^2$ above the upper edge of the highest bin in $M_{\ell b}^2$, that is the overflow events, are included in that bin. The binning of the 2-D $M_{\ell b}^2$ distributions is non-equidistant and has been optimized with the criterion of a minimum statistical significance of ≈20% in all the bins of the most statistically-limited background template.

Note that pseudo-experiment studies show that the statistical sensitivity in the dilepton channel without $b$-tagging is approximately 40% better than when requiring at least one $b$-tagged jet. Although the background is negligible in the $b$-tagged sample, this analysis is statistically limited, so we choose to not require $b$-tagging information. As for the lepton plus jets channel, the signal $t\bar{t}$ Monte Carlo samples for V+A and V-A $M^2_{\ell b}$ templates have been generated with high statistics using the MC generator Alpgen [11] for the hard process in combination with Pythia [13] for hadronization.

The Drell-Yan and diboson dilepton background templates are modeled by Alpgen+Herwig with 2 partons. The fake lepton background is purely data based: the kinematics are derived from a sample of dilepton events $\ell + d$ found in the signal samples that passed the complete top dilepton event selection with $\ell$ being an identified electron or muon, and $d$ being an object in the detector that could fake the signature of a identified lepton $e, \mu$: a jet with $E_{HAD}/E_{EM} < 0.5$ or a track with $E/P < 1$. When building the $M^2_{\ell b}$ background template, each of these fake-able dilepton events are weighted with the corresponding fake lepton probabilities derived from a single jet trigger data sample with a threshold of $E_T = 50$ GeV, where the $P_T$ spectrum of the $d$ objects is found to be similar to the one in the signal samples. Given the high efficiency in background rejection obtained by the dilepton cross section analysis [14] and the statistical limitations affecting the 2-D $M^2_{\ell b}$ background templates, each individual background template ($Z^*/\gamma \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$, fake lepton, and $WW/WZ$ ) is combined into one total dilepton background template with relative proportions $\sim 50\%$ from $Z^*/\gamma \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$, $\sim 30\%$ from fake leptons, and $\sim 20\%$ from $WW/WZ$.

## V. THE LIKELIHOOD FIT TECHNIQUE

### A. The likelihood function

A binned log likelihood fit procedure is used to extract the fraction $f_{V+A}$ in data. The binned distributions of $M^2_{\ell b}$ are obtained for the three independent samples: (i) lepton plus jets with one $b$-tagged jet, (ii) lepton plus jets with two $b$-tagged jets and (iii) dileptons. There is one *parameter of interest*: $f_{V+A}$. Additional *nuisance parameters* are the total background cross sections for each sample $\sigma_{bg}$ and the $t\bar{t}$ cross section $\sigma_{t\bar{t}}$.

The analytic expression for the likelihood for each sample (Eq.2) is the product over the total $N$ bins in $M^2_{\ell b}$ of the Poisson probabilities of observing $n_i$ events in a given bin $i$ when the average expected bin content is $\mu_i$, and a Gaussian constraint on the total background cross section for the sample:

$$\mathcal{L}_{sample} = \Big[\prod_{i=0}^{N_{bins}} P(n_i, \mu_i)\Big] \times \Big[G(\sigma_{bg}, \epsilon_{\sigma bg})\Big] \tag{2}$$

The expectation for $\mu_i$ depends on the free parameters in the fit $f_{V+A}$, $\sigma_{bg}$, $\sigma_{t\bar{t}}$ and the acceptances for V+A and V-A through the sequence of equations 3 and 4-6. Here the $x_{V+A}, x_{V-A}$ and $x_{bg}$ are the expected fractions of $t\bar{t}$ V+A, $t\bar{t}$ V-A and background. The $\hat{T}^i_{V+A}$,$\hat{T}^i_{V-A}$ and $\hat{T}^i_{bg}$ are the probabilities for an event to land in bin $i$ of the $M^2_{\ell b}$ distribution for $t\bar{t}$ V+A, $t\bar{t}$ V-A and background. In each case, the $\sum_i \hat{T}^i = 1.0$. The $N^{data}$ is the observed total number of data events for the sample.

$$\mu_i = N^{data}\Big[x_{V+A} \times \hat{T}^i_{V+A} + x_{V-A} \times \hat{T}^i_{V-A} + x_{bg} \times \hat{T}^i_{bg})\Big] \tag{3}$$

$$x_{bg} = \frac{\sigma_{bg}}{\sigma_{bg} + \sigma_{t\bar{t}}[Acc^{V+A} f_{V+A} + Acc^{V-A}(1 - f_{V+A})]} \tag{4}$$

$$x_{V+A} = \frac{f_{V+A} Acc^{V+A} \sigma_{t\bar{t}}}{\sigma_{bg} + \sigma_{t\bar{t}}[Acc^{V+A} f_{V+A} + Acc^{V-A}(1 - f_{V+A})]} \tag{5}$$

$$x_{V-A} = \frac{(1 - f_{V+A}) Acc^{V-A} \sigma_{t\bar{t}}}{\sigma_{bg} + \sigma_{t\bar{t}}[Acc^{V+A} f_{V+A} + Acc^{V-A}(1 - f_{V+A})]} \tag{6}$$

The general analytic expression for the combined likelihood is the product of each individual likelihood sample and a common Gaussian constraint due to the limited knowledge of the theoretical $t\bar{t}$ cross section:

$$\mathcal{L}_{combined} = \prod_{samples} \mathcal{L}_{samples} \times G(\sigma_{t\bar{t}}, \sigma_{exp.t\bar{t}}, \epsilon_{\sigma_{t\bar{t}}}) \tag{7}$$

The set of ingredients going into the likelihood function are thus:

- The signal V-A,V+A and background template distributions for the three samples: lepton plus jets with 1 $b$-tagged jet, lepton plus jets with 2 $b$-tagged jets, and dileptons. These distributions are shown in Figure 1.
- Acceptances for V-A and V+A $t\bar{t}$ events as given in Sections III A and IV A.
- Effective cross-sections for background as given in Sections III A and IV A.
- The theoretical prediction for the $t\bar{t}$ production cross section: 6.7 pb (see theory references [15]) and an uncertainty on 1 pb in the $t\bar{t}$ production cross section covering both the theoretical accuracy and the acceptance uncertainty.

### B. Testing the fitting method and sensitivity studies

Ensembles of MC events or *pseudo-experiments* are performed to test the robustness of the fitting procedure. For a given pseudo-experiment and a particular sample, the total number of observed events in data $N_{DATA}$ is distributed in three categories ($t\bar{t}$ V+A, $t\bar{t}$ V-A and background) through a binomial deviate according to the appropriate probability from the expected fractions of each category. These probabilities are first fluctuated with a Gaussian to incorporate the uncertainty in the effective background cross sections as well as in the $t\bar{t}$ cross section (see Eq (2) and (7) ). For each category the number of actual events are distributed in the $M^2_{\ell b}$ space randomly according to the parent distributions in Figure 1.

The hypotheses that $f_{V+A}$=0.0, 0.1, 0.2,...,0.9, 1.0 are studied for 1000 pseudo-experiments for the three samples separately as well as for all samples combined together. In all cases, the pseudo-experiment studies showed that the fit is unbiased and stable. The residual of the mean fitted value for $f_{V+A}$ compared to the hypothesis, and the mean and the width of the pull distribution are shown in Figure 2 for all samples combined together. An expected statistical uncertainty of $\pm 0.22$ on $f_{V+A}$ is found for the combined sample, as shown in Figure 3. Individual statistical uncertainties are 0.36, 0.41 and 0.49 for lepton plus jets single $b$-tagged events, lepton plus jets double $b$-tagged events, and dilepton events, respectively.

### C. Expected 95% Confidence Level and Coverage

For a given $f_{V+A}$ hypothesis and for each pseudo-experiment, the 95% CL is evaluated using a Bayesian approach. Firstly, the profile likelihood function is determined as a function of $f_{V+A}$. Then the profile likelihood is multiplied by a prior that is a flat function of $f_{V+A}$ between 0 and 1, the physical boundaries. After normalizing to unity, the 95% CL of that particular pseudo-experiment is the value of $f_{V+A}$ yielding 0.95 of the integral. A distribution for the 95% CL is obtained from 2000 pseudo-experiments. This is shown in Figure 4 for the hypothesis $f_{V+A}$=0.0, where the mean expected 95% CL is 0.36 with an RMS of 0.16.

The coverage probability is defined as the fraction of those 95% CL limits that included the $f_{V+A}$ hypothesis. A 2-D contour plot (see figure 5) is generated by repeating the whole exercise in discrete steps of the $f_{V+A}$ hypothesis (*x-axis*), and plotting selected percentiles of the 95% CL distributions (*y-axis*).

A 95% CL will be set by integrating the profile likelihood resulting from the data fit from 0.0 to a value of $f_{V+A}$ that yields 95% of the integral between 0.0 and 1.0. The coverage of the measured value should not be significantly lower than 95%, otherwise a correction would be necessary to restore coverage.

## VI. SYSTEMATIC UNCERTAINTIES

### A. Methodology and sources.

The effect of a change in the systematic parameters is modeled by (i) a shift in the mean of the 95% CL limit from a set of 2000 pseudo experiments, and (ii) as a shift in the measured value of $f_{V+A}$ from the same set of 2000 pseudo experiments. The systematic shifts are evaluated at $f_{V+A} = 0$ since none of the existing systematic sources are related to the structure of the $t$-$W$-$b$ vertex. For a given source of systematics, 2000 pseudo-experiments are built considering a new $t\bar{t}$ V-A MC sample that is produced with the convenient parameter changed to account for the systematic shift under evaluation. After applying the fitter technique described in section V where the $t\bar{t}$ V+A,V-A and background templates (see fig 1) in equation 3 are kept constant under all circumstances, the systematic shifts are quantified.

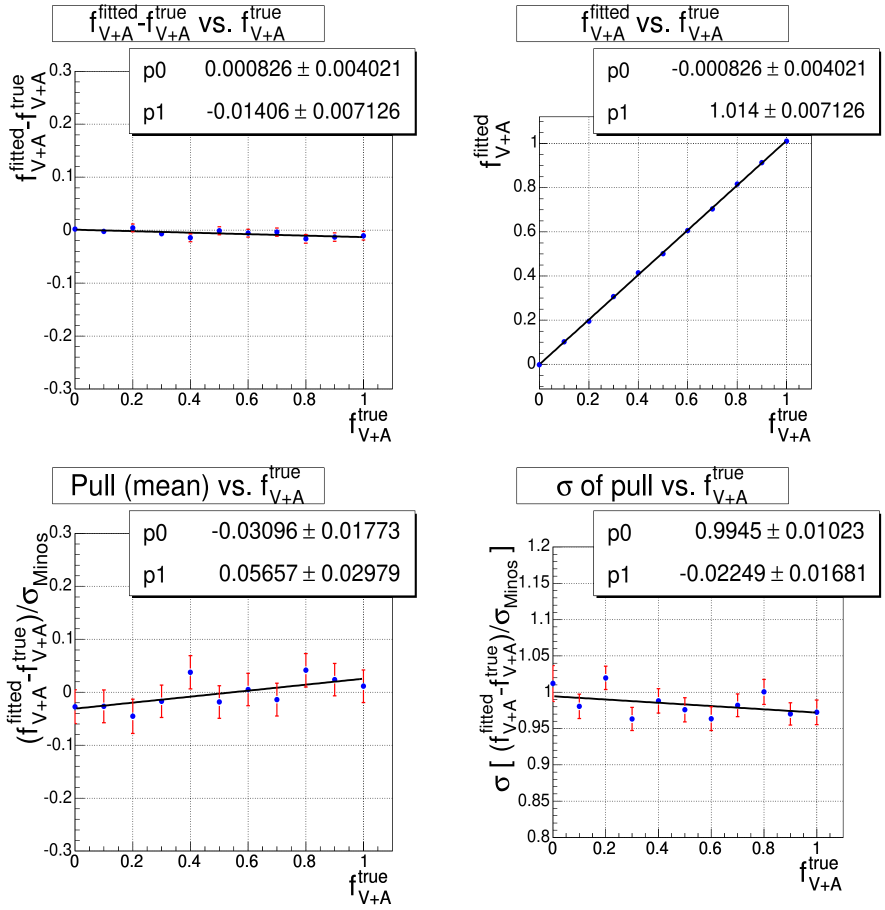


FIG. 2: The bias, fitted vs true, mean and sigma of pull for the three samples combined: lepton plus jets with one $b$-tagged jet, lepton plus jets with two $b$-tagged jets and dileptons.

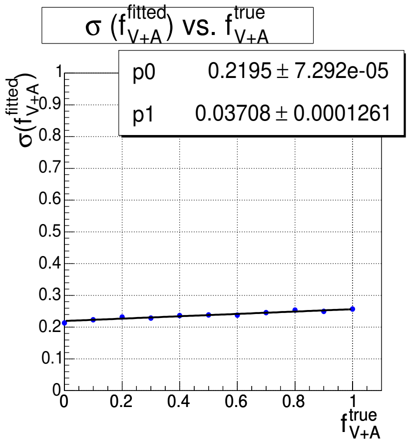


FIG. 3: The expected statistical uncertainty $\sigma(f_{V+A})$ on the fitted value for $f_{V+A}$ using the three samples combined: lepton plus jets with one $b$-tagged jet, lepton plus jets with two $b$-tagged jets and dileptons. The non-zero slope is due to the different acceptances of the V-A and V+A samples.

The main systematic sources in the measured value for $f_{V+A}$ are summarized in Table I. The most important one is the systematic uncertainty on the jet energy [16]. For its evaluation the energy of the jets is varied $\pm 1\sigma$ for $t\bar{t}$ and background total rates and distributions. The second biggest systematic uncertainty is due to the modeling of the background $M^2_{\ell b}$ distribution. In the lepton plus jets channel this comes mainly from uncertainties in the rate and the

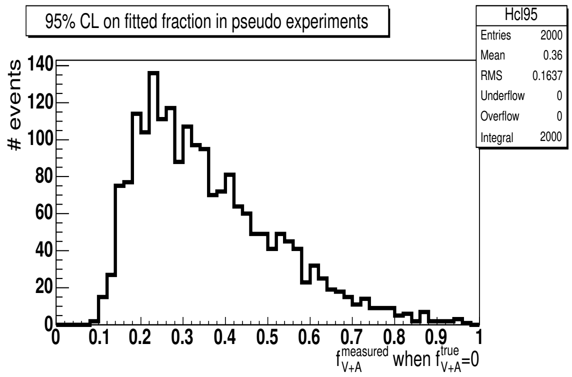


FIG. 4: The expected 95% CL limit as obtained when using the $f_{V+A}$=0.0 hypothesis.

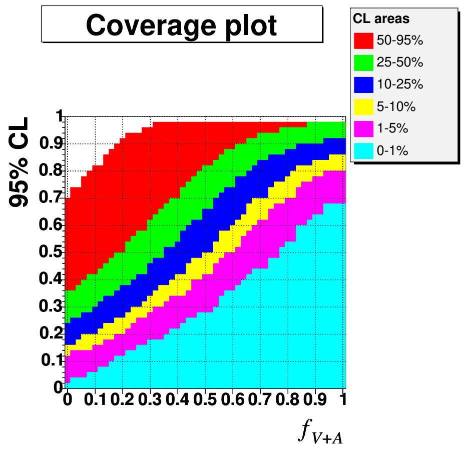


FIG. 5: The CL contours as function of $f_{V+A}$.

$M_{\ell b}^2$ distribution for the QCD background, and also from the $Q^2$ dependence of the $M_{\ell b}^2$ distribution for $W + b\bar{b} + 1p$ Monte Carlo samples. In the dilepton channel it results mainly from the $E_T$ trigger threshold of the jet samples used to measured the lepton fake probabilities that weighted the fake-able dilepton events (see subsection IV B) used to model $M_{\ell b}^2$ distribution.

### B. Incorporation into the CL limit.

All systematic effects have been incorporated into the 95% CL using a Bayesian approach. In the cases where the shift is symmetric, the effect of the uncertainty on the 95% CL is approximated by convoluting the 95% CL limit obtained from the nominal pseudo-experiments (i.e. drawn from the default samples) with a Gaussian deviate of mean zero and sigma given by the absolute value of the shift. In cases where the shift is not symmetric, a non-zero mean is taken. The 95% CL limit is then smeared according to a Gaussian with mean $\mu_{tot}$ and sigma $\sigma_{tot}$ given by:

$$\mu_{\rm tot} = \sum_i \mu_i \tag{8}$$

$$\sigma_{\rm tot} = \sqrt{\sum_i \sigma_i^2} \tag{9}$$

where $\mu_i$ and $\sigma_i$ are the mean and sigma values calculated for systematic effect $i$. This is incorporated in the coverage plot in Figure 5.

| Source | Uncertainty |
|---|---|
| Jet Energy Scale | 0.10 |
| Background modeling | 0.04 |
| MC statistics | 0.04 |
| $b$-tagging | 0.02 |
| ISR/FSR | 0.02 |
| Minimum bias | 0.02 |
| Generator | 0.01 |
| PDFs | 0.01 |
| Total | 0.12 |

TABLE I: A summary of the most important systematic uncertainties in the measured value for $f_{V+A}$.

## VII. RESULTS AND CONCLUSIONS.

In 695 pb$^{-1}$, there are 304 $t\bar{t}$ lepton plus jets candidates with exactly 1 $b$-tagged jet found with a total expected background of 88.5±11.2 events, and 75 $t\bar{t}$ lepton plus jets candidates found with exactly 2 $b$-tagged jets with a total expected background of 9.1±1.8 events. There are 64 $t\bar{t}$ dilepton candidates found in 750 pb$^{-1}$(12 $ee$, 24 $\mu\mu$ and 26 e$\mu$) with a total background of 20±4 events. The good agreement between data and total SM Monte Carlo expectations in the $M^2_{\ell b}$ distributions is shown in Figures 6, 7, and 8.

We quote our result at a top quark mass value of 175 GeV/$c^2$. The dependence of our result on the top quark mass is given in Table III. The binned likelihood fit for the lepton plus jet sample (single and double $b$-tagged combined) results in a measured value of

$$f_{V+A} = 0.21 \pm 0.28. \tag{10}$$

where the uncertainty comes from the fit, i.e. it includes the statistical uncertainty and the uncertainties on the $t\bar{t}$ and effective lepton plus jets background cross sections. For the dilepton channel we obtain

$$f_{V+A} = -0.64 \pm 0.37. \tag{11}$$

where the uncertainty comes again from the fit, i.e. it includes the statistical uncertainty and the uncertainties on the $t\bar{t}$ and effective dilepton background cross sections. Note that this low value for $f_{V+A}$ is consistent with the low value for the top quark mass measured from the same events in the dilepton channel by CDF [17]. However this effect is not statistically significant. Taking into account all three samples and adding the total systematic uncertainty as obtained from Table I, the combined result of the fit for the measured fraction of V+A is

$$f_{V+A} = -0.06 \pm 0.25(\text{ stat.+syst.}) \tag{12}$$

This value is in agreement with the Standard Model. Table II summarizes the values measured for the nuisance parameters.

In absence of a signal, a 95% CL limit is obtained for the combined result by studying the profile likelihood from data. The result obtained from the fit is

$$f_{V+A} < 0.29 \text{ at } 95\% \text{ CL}. \tag{13}$$

No correction for the coverage is necessary. To compare with results for $f^+$, the fraction $f^+$ of right-handed $W^+$ bosons (left-handed $W^-$ bosons), we translate our $f_{V+A}$ result into $f^+$ by remembering that $f_{V+A} = f^+/0.3$ (if indeed $f^0 = 0.7$). We obtain $f^+$ = -0.02 ± 0.07 and $f^+ < 0.09$ at 95% CL.

| Nuisance parameter | Input value | Fitted value |
|---|---|---|
| $tt$ cross section (pb) | 6.7 ± 1.0 | 7.26 ± 0.93 |
| Effective background cross section SVX1 (pb) | 0.156 ± 0.017 | 0.154 ± 0.016 |
| Effective background cross section SVX2 (pb) | 0.013 ± 0.002 | 0.013 ± 0.002 |
| Effective background cross section DIL (pb) | 0.026 ± 0.006 | 0.022 ± 0.006 |

TABLE II: The input values and fitted values for the nuisance parameters in the fit for all samples.

| Top Quark Mass (GeV/$c^2$) | Shift in $f_{V+A}$ | Shift in 95% CL |
|---|---|---|
| 172.5 | -0.09 | -0.07 |
| 177.5 | +0.09 | +0.07 |

TABLE III: Dependence of $f_{V+A}$ on assumed value of top quark mass, relative to central value of 175 GeV/$c^2$.

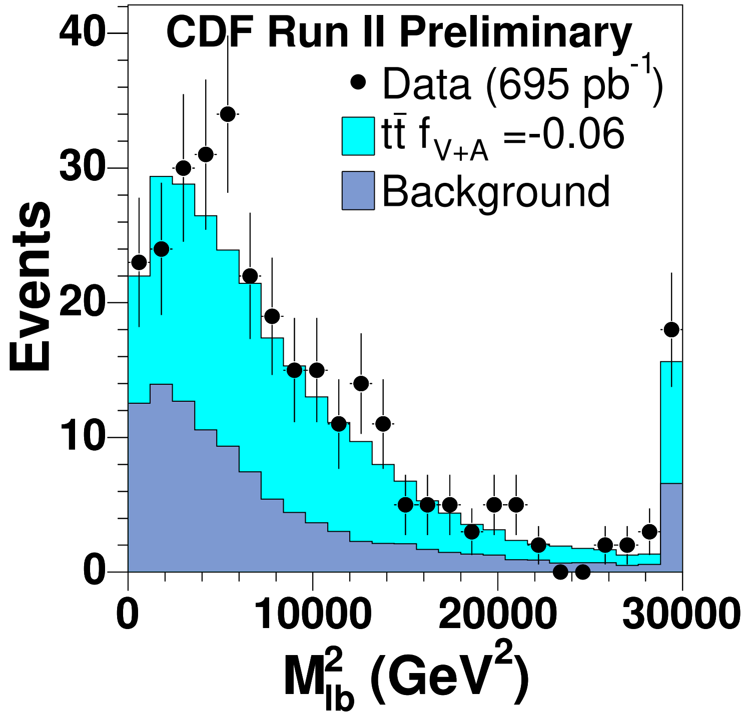


FIG. 6: 1-D $M^2_{\ell b}$ distributions for the *lepton plus jets single b-tagged* sample. Data in black dots. Background in dark blue solid histograms.

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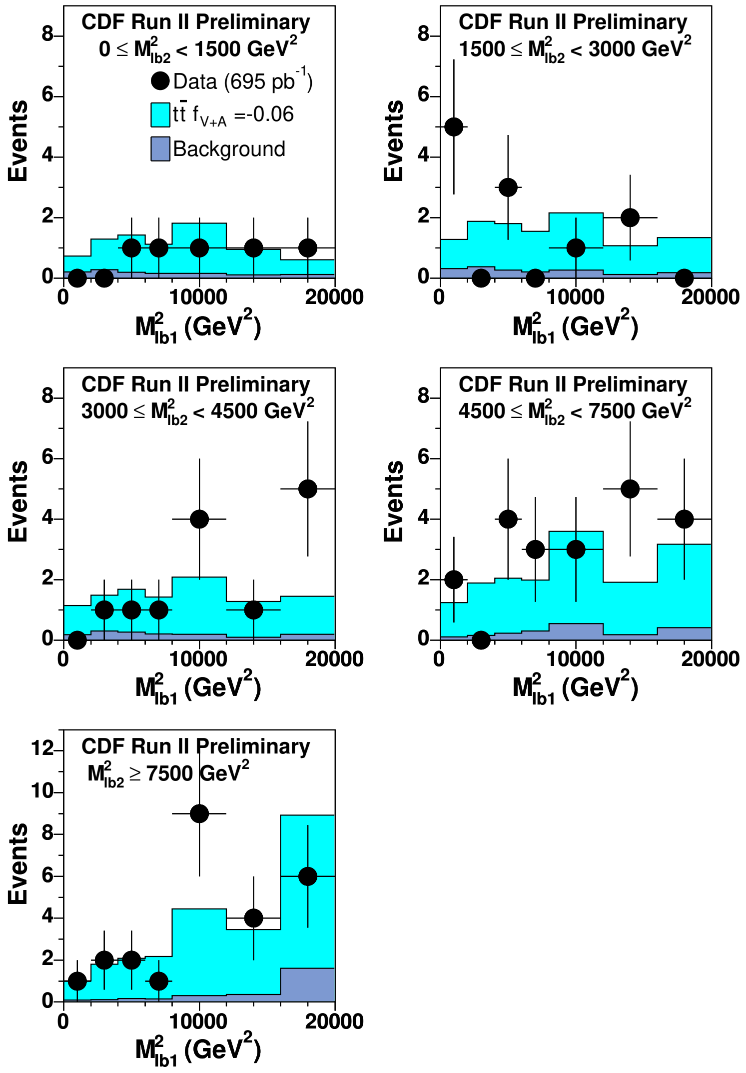


FIG. 7: 1-D $M^2_{\ell b}$ projections for each y-bin of the 2-D *lepton plus jets double b-tagged* $M^2_{\ell b}$ distribution. Data in black dots. Background in dark blue solid histograms.


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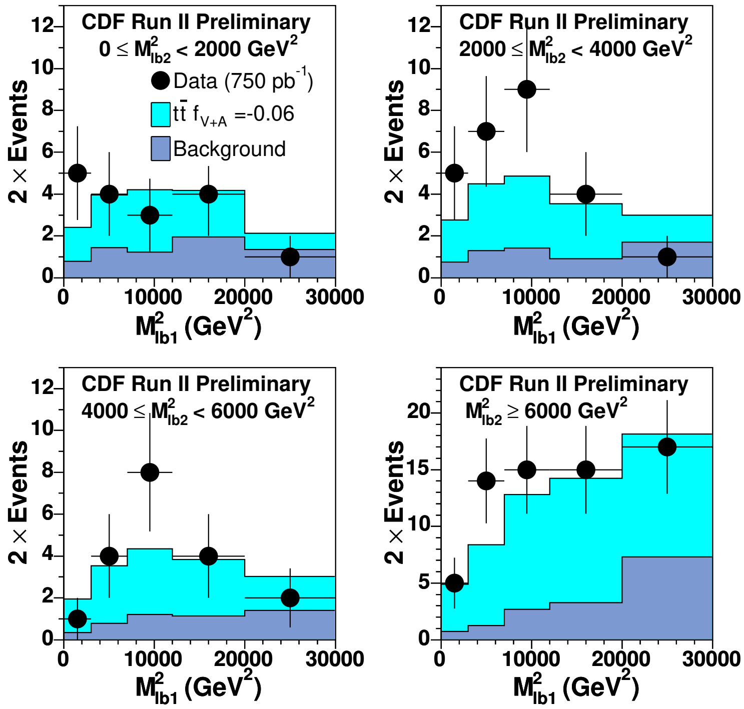


FIG. 8: 1-D $M^2_{\ell b}$ projections for each y-bin of the 2-D *dilepton* $M^2_{\ell b}$ distribution. Data in black dots. Background in dark blue solid histograms.