Measurement of the W Boson Polarization in Top Decay at CDF at $\sqrt{s} = 1.8$ TeV

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Abstract

The polarization of the W boson in $t \to Wb$ decay is unambiguously predicted by the Standard Model of electroweak interactions and is a powerful test of our understanding of the tbW vertex. We measure this polarization from the invariant mass of the b quark from $t \to Wb$ and the lepton from $W \to l\nu$ whose momenta measure the W decay angle and direction of motion, respectively. In this paper we present a measurement of the decay rate (f_{V+A}) of the W produced from the decay of the top quark in the hypothesis of V+A structure of the tWb vertex. We find no evidence for the non-standard V+A vertex and set a limit on $f_{V+A} < 0.80$ at 95% confidence level. By combining this result with a complementary observable in the same data, we assign a limit on $f_{V+A} < 0.61$ at 95% CL. This corresponds to a constraint on the right-handed helicity component of the W polarization of $f_+ < 0.18$ at 95% CL. This limit is the first significant direct constraint on f_{V+A} in top decay.

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The large value of the top quark mass has led to speculation that the top quark could play a role in the mechanism of the electroweak symmetry breaking [1]. If so, the electroweak interactions of the top quark could be modified [2]. Such a modification could alter the V$-$A structure of the tbW interaction which in turn would lead to an altered W polarization in top decay [3–5]. Possible scenarios that would introduce a V+A contribution to the tbW vertex include $SU(2)_L \times SU(2)_R$ extensions of the standard model [6]. One such model invokes new mirror particles to assist a top-condensate in breaking electroweak symmetry [7]. The theory of "beautiful mirror" fermions predicts a fourth generation up-type quark with right-handed weak interactions which could contaminate the top sample or induce a right-handed top electroweak interaction by mixing with the top quark [8].

Indirect limits of right-handed $t \rightarrow bW$ currents have been placed using the process $b \rightarrow s\gamma$, which proceeds via an electroweak radiative penguin process [9]. These limits are stringent, but scenarios can be envisaged where other contributions to $b \rightarrow s\gamma$ might invalidate these bounds. The goal of this study is a direct measurement of the tbW vertex from the electroweak decay of top.

The spin-one W has three possible helicities; for the W^+ we label these as -1 (left-handed), 0 (longitudinal), and $+1$ (right-handed), with the opposite convention for the W^-. Because $M_t > M_W$, a large fraction of the W bosons produced in top decay will be longitudinally polarized [3]. The fraction is given by

$$F_0 = \frac{M_t^2/M_W^2}{(M_t^2/M_W^2 + 2)}. \tag{1}$$

For the current values of $M_t = 174.3 \pm 5.1$ GeV and $M_W = 80.425 \pm 0.038$ GeV [10], this corresponds to $F_0 = 0.70 \pm 0.01$. If there were a non-standard model V+A contribution to the top decay vertex, such contribution would not decrease the branching ratio to longitudinal W bosons but would instead decrease the branching ratio to left-handed W bosons, replacing some of this rate with an enhanced right-handed component.

Leptons from the decay of longitudinally polarized W bosons have a symmetric angular distribution of the form $1 - (\cos\psi_\ell^\star)^2$, where $\psi_\ell^\star$ is defined as the angle in the W rest frame between the lepton and the boost vector ($\vec{\beta}$) from the top rest frame to the W rest frame. Maximal parity violation in the V$-$A electroweak theory predicts that the non-longitudinal W helicity is purely left-handed in the limit of massless final state fermions. This creates an

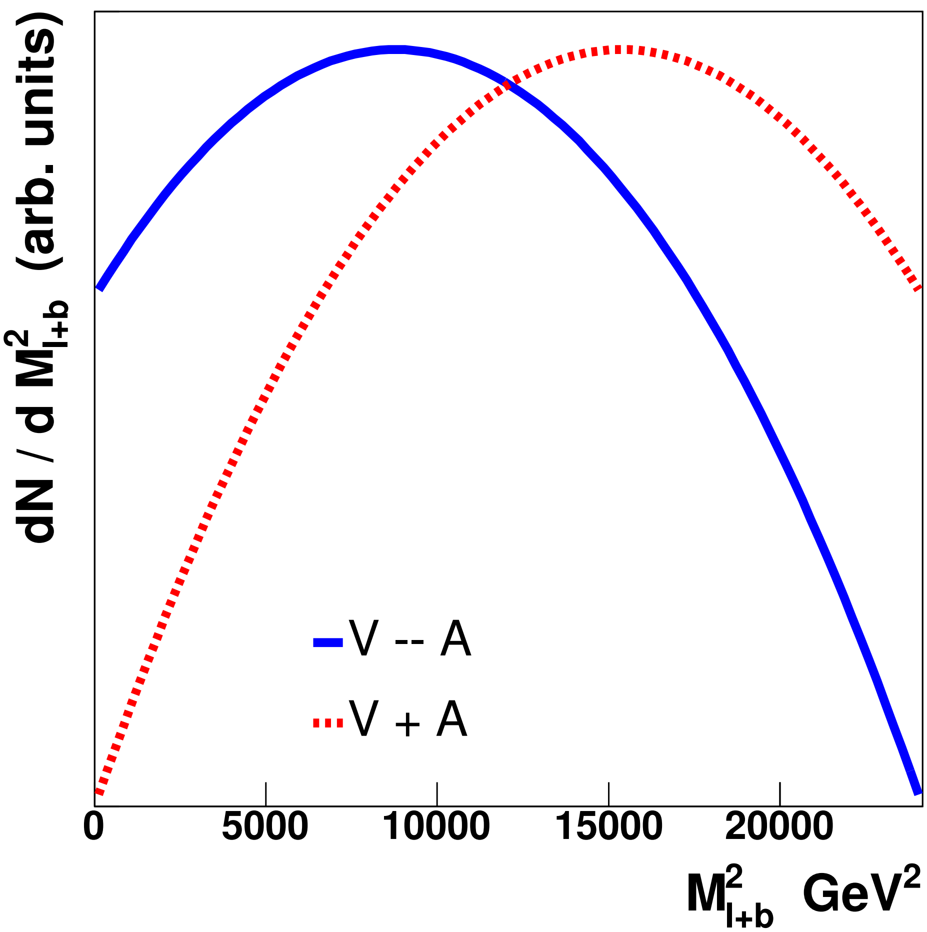

Figure 1: The theoretical distributions of $M^2_{\ell b}$ for purely V−A and V+A hypotheses, using the correct lepton-b pairing. The $M^2_{\ell b}$ can be used to discriminate between the two hypotheses as it peaks at higher values for V+A. This ideal case does not include detector and trigger effects or the intrinsic lepton-b mass resolution.

asymmetric angular distribution of the form $(1-\cos\psi^\star_\ell)^2$ [3]. Due to angular momentum conservation, even though the massive top quark may be left- or right-handed, positively polarized W^+ bosons are not possible since a massless b quark must be left-handed. A small right-handed component (0.04 %) of the form $(1+\cos\psi^\star_\ell)^2$ results when the mass of the b quark is considered.

This analysis exploits the relationship between the angle $\psi^\star_\ell$ and the invariant mass of the ℓb pair, produced in the top decay chain $t \to Wb$, $W \to \ell\nu$ to determine the polarization of the W boson. The angle $\psi_\ell^\star$ can be related to the ℓb invariant mass by

$$M_{\ell b}^2 = \frac{1}{2}(M_t^2 - M_W^2)(1 + \cos\psi_\ell^\star). \quad (2)$$

In the V−A theory, the lepton and b jet in the W rest frame tend to move in the same direction, but in a V+A decay, the lepton and b jet typically move in opposite directions. Therefore, $M_{\ell b}^2$ would be larger on average from a V+A contribution as shown in Fig. 1. This difference can be used to determine f_{V+A}, the fraction of t quarks which decay with a V+A interaction.

If the interaction has both V−A and V+A contributions, the total angular distribution will be approximately described by summing over weighted linear combinations of the above angular distributions. The summing of rates correctly describes the angular distribution from longitudinal and either a pure V+A or V−A distribution; however, if there is a combination of V−A and V+A interactions, they may interfere with some relative phase. The present analysis neglects this interference, which would have the largest impact for $f_{V+A} = 0.5$. These interference effects are only of order $1/\gamma_b$, the boost of the b quark in the top rest frame, and therefore are estimated to affect the angular distributions [11] at no more than the 10% level. The associated uncertainty is therefore not significant compared to expected statistical and systematic uncertainties.

Experimentally, $M_{\ell b}^2$ is a reliable observable in $t\bar{t}$ decay at a hadron collider because no information about the top or W rest frames is required, and therefore the unknown boost of the $t\bar{t}$ system along the beam direction does not disrupt the measurement. This technique also avoids the need to rely on the missing transverse energy ($\not\!\!E_T$) due to the neutrino. The $\not\!\!E_T$ is poorly measured compared to other kinematic quantities in the event and is ambiguous in events with two final state neutrinos, e.g., both W^+ and W^- from the $t\bar{t}$ decay leptonically.

The present study uses data from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected by the Collider Detector at Fermilab (CDF)[12] during the period 1992-1995 (Run I). The integrated luminosity of the data sample is 109 ± 7 pb^{-1}. Events were selected [13, 14] and assigned to three different $t\bar{t}$ subsamples chosen for their low background and high efficiency for b jet identification. Each sample is classified by the number of leptons and identified b jets in the final state.

The "dilepton" sample is dominated by $t\bar{t}$ in which both W bosons decay to an electron or muon and neutrinos. Events are selected by requiring $\not\!\!E_T > 25$ GeV, one muon and one electron of opposite charge with $P_T > 20$ GeV in the central pseudo-rapidity region ($|\eta| < 1.0$) [15], and two jets with $E_T > 10$ GeV and $|\eta| < 2.0$. This is a subsample of the dilepton events used in other analyses [14], considering only $e + \mu + jets$ events in order to remove the dominant background, which is Drell-Yan production of ee or $\mu\mu$. The significant remaining backgrounds are decays to electron and muon of $Z \rightarrow \tau\tau$, WW in association with extra jets, and W production associated with three or more jets, where one jet is misidentified as an electron or a muon. No attempt is made to identify b jets explicitly. However, initial and final state gluon radiation can result in extra jets, so the b jets are assumed to be the two highest E_T jets, which is correct in ∼80 % of dilepton events. There are four $M_{\ell b}$ combinations in each dilepton event.

The other two samples used in the analysis require only one W to decay into an electron or muon and a neutrino and the other W to decay hadronically ("lepton+jets"). These events are selected by requiring one electron or muon with $P_T > 20$ GeV, in the central region as above. At least four jets are required, three of which must have $E_T > 15$ GeV, $|\eta| < 2.0$, and the fourth must have $E_T > 8$ GeV and $|\eta| < 2.4$. The background for these events consists predominantly of direct production of a W plus extra jets and its behavior is modeled with the VECBOS generator [16]. To reduce the background, at least one jet must be identified as a b candidate (b-tagged) with a topological algorithm requiring tracks in the jet reconstructed with the silicon vertex (SVX) detector to form a secondary vertex [13, 17]. This requirement is 48 % efficient for tagging at least one b jet in a $t\bar{t}$ event [18]. Without any b-tag, the expected signal to background ratio (S/B) of the sample is 0.4, whereas requiring one b-tag improves S/B to 5.3. The b-tag also selects the jet to be paired with the lepton to form $M_{\ell b}$. Events with a single b-tagged jet comprise the "single-tagged" sample, and have one measured $M_{\ell b}$ which is correct half the time. Events with both b quarks tagged make up the "double-tagged" sample, have a S/B of 24, and provide two $M_{\ell b}$ pairings, at least one of which combines the wrong b with the ℓ.

A total of 7 events were found in the dilepton $e\mu$ sample with an expected background of 0.76 ± 0.21 events. In the single-tagged sample 15 events were found with a background 2.0 $\pm$ 0.7, and in the double-tagged sample there were 5 events with a 0.2 ± 0.2 background. Note that since right-handed leptons have higher P_T, an increase in events passing the lepton P_T trigger requirement could also indicate a V+A theory. However, any potential observed

Systematic Uncertainties	
Top mass	0.19
Jet energy scale	0.04
Background shape	0.05
Background normalization	0.05
ISR gluon radiation	0.04
FSR gluon radiation	0.03
B tagging efficiency	0.03
Parton distribution functions	0.02
Monte Carlo statistics	0.01
Relative acceptance	0.005
Total systematic	0.21

Table I: Summary of systematic uncertainties in terms of the shift in measurement of the V+A fraction. The systematic uncertainties shown for the top mass and jet energy scale are after considering the correlations between the two; without these corrections the systematic uncertainties are 0.21 and 0.14, respectively.

rate increase would be deemed to be *a posteriori* knowledge from the point of view of this analysis, and therefore only the shape of the $M^2_{\ell b}$ distributions is considered.

The $M^2_{\ell b}$ distributions of the data are fit to a linear combination of three predicted $M^2_{\ell b}$ distributions: $t\bar{t}$ production with a V−A interaction, $t\bar{t}$ production with a V+A interaction, and background. The fit maximizes a binned likelihood as a function of f_{V+A}. Likelihood scans are performed both inside and outside the physical region of $[0, 1]$ in f_{V+A}, and the level of backgrounds in each fit is allowed to vary within the estimated uncertainties.

The predicted $M_{\ell b}$ distributions are calculated separately for dilepton, single-tagged, and double-tagged data samples, by Monte Carlo simulations of $t\bar{t}$ and background. The effects of predicted kinematics, decay distributions, detector acceptance, and resolution are all considered. The HERWIG event generator [19] with the MRST h-g PDF set [20] was used to model $t\bar{t}$ production.

For cases with two possible b jets that can be matched to a lepton (the dilepton and double-tagged samples), the fit is performed to two-dimensional distributions of $M^2_{\ell b_{(1)}}$ and $M^2_{\ell b_{(2)}}$, thus taking into account that only one can be correct. Naively, this ambiguity in assignments of leptons and b quarks to one top quark would appear to be problematic in this measurement. However, while correct pairings are limited kinematically by $M_t^2 - M_W^2$ for a massless b quark, incorrect pairings often have significantly higher mass. With our two dimensional fit, mispairings only increase the statistical uncertainty in the fit by only 15%.

Systematic uncertainties in the measurement enter the analysis primarily through the prediction of the $M_{\ell b}$ distributions, and are evaluated by changing assumptions in the Monte Carlo simulation. Listed individually in Table I, all systematic uncertainties added in quadrature represent a 0.21 uncertainty in f_{V+A}. The largest systematic uncertainties are from the top mass and the jet energy scale. Increasing the top mass will increase $M_{\ell b}$ in top decay. The measured uncertainty of the top quark mass is 5.1 GeV [21], and an increase in top mass by one standard deviation increases f_{V+A} by 0.19. Sources of systematic uncertainty in the jet energy scale include the calibration of the calorimeter, the simulation of the calorimeter response and the modeling of fragmentation [13]. An increase in the overall jet energy scale by one standard deviation would increase f_{V+A} by 0.14. However, the CDF jet energy scale has a large effect on the world average top mass measurement. Accounting for the correlation between these two effects results in a reduction of the systematic from jet energy scale to 0.04.

Smaller sources of systematic uncertainties were studied in this measurement by observing the effect in simulated pseudoexperiments. Hard gluon bremsstrahlung either in the initial or final state can cause significant mismeasurement of the b quark jet or can produce a jet which can be mistaken for the b quark jet itself. The size of the effect was conservatively estimated by removing all such events from the sample in a simulated measurement. For samples where SVX topological b tagging was used, the effect of uncertainties in b tagging efficiency as a function of b jet E_T were evaluated. Estimated background rates and distributions in $M^2_{\ell b}$ were varied as well. The most important of these effects is the uncertainty in the mean Q^2 used in the VECBOS simulation of the W+jets background as discussed in Ref. [18]. A set of CTEQ [22] and MRST [20] Parton Distribution Functions (PDFs) were compared to the standard PDF set of MRST h-g and found to cause a small spread in the measured f_{V+A}. Systematic uncertainty due to the limited size of the Monte Carlo simulation samples is also included.

The data and expected Standard Model distributions are shown for each of the three samples in Fig. 2. We can combine the statistical likelihood as a function of f_{V+A} for each sample into the joint likelihood shown in Fig. 3. The combined result for f_{V+A} and its 1σ uncertainties are

$$f_{V+A} = -0.21^{+0.42}_{-0.24}(\text{stat.}) \pm 0.21(\text{syst.}) \tag{3}$$

The central value depends on the true top mass, $f_{V+A}(M_t) = -0.21 + 0.037(M_t - 174.3$

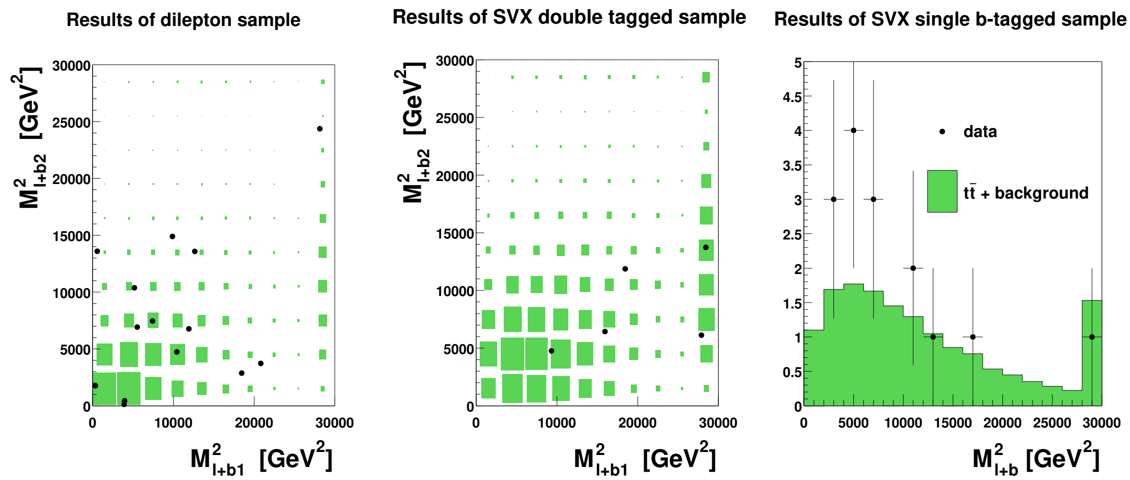

Figure 2: Data and Standard Model Monte Carlo distributions for each sample. The last bin includes combinations greater than 30,000 GeV^2, which are predominantly the result of incorrect pairings. Errors are statistical only.

GeV), and the top mass uncertainty is reflected in the systematic error. This central value lies in an unphysical region, but is more consistent with a Standard Model V−A interaction for the tbW vertex than a V+A interaction. We can place a one-sided upper limit on the fraction of rate due to a V+A component by construction of a Neyman confidence band in the variable f_{V+A} [23]. This procedure results in an upper limit on f_{V+A} of 0.80 at 95% confidence level. With the assumption of a standard model longitudinal helicity fraction, this corresponds to $f_+ < 0.24$ at 95% confidence level.

W polarization in top decays has also been studied at CDF in the same data sample using the lepton P_T [24] as the observable to discriminate between left-handed and right-handed W bosons, under the assumption of a fixed longitudinal helicity. These two results have different selection criteria, but share largely overlapping data sets. In addition, the observables themselves are weakly correlated, and a large fraction of the systematic uncertainties are common. Nevertheless, the overall statistical correlation of the two results is only about 0.4. Under the simplifying assumption of Gaussian uncertainties, the combined measurement using both the $M_{\ell b}$ and lepton P_T approaches is that the fraction of W bosons produced in a V+A interaction is

$$f_{V+A} = -0.07 \pm 0.37(\text{stat.} \oplus \text{syst.}). \tag{4}$$

The combined upper limit is $f_{V+A} < 0.61$ at 95% confidence level. In terms of the right-handed helicity fraction, this corresponds to $f_+ < 0.18$ at 95% confidence level. The com-

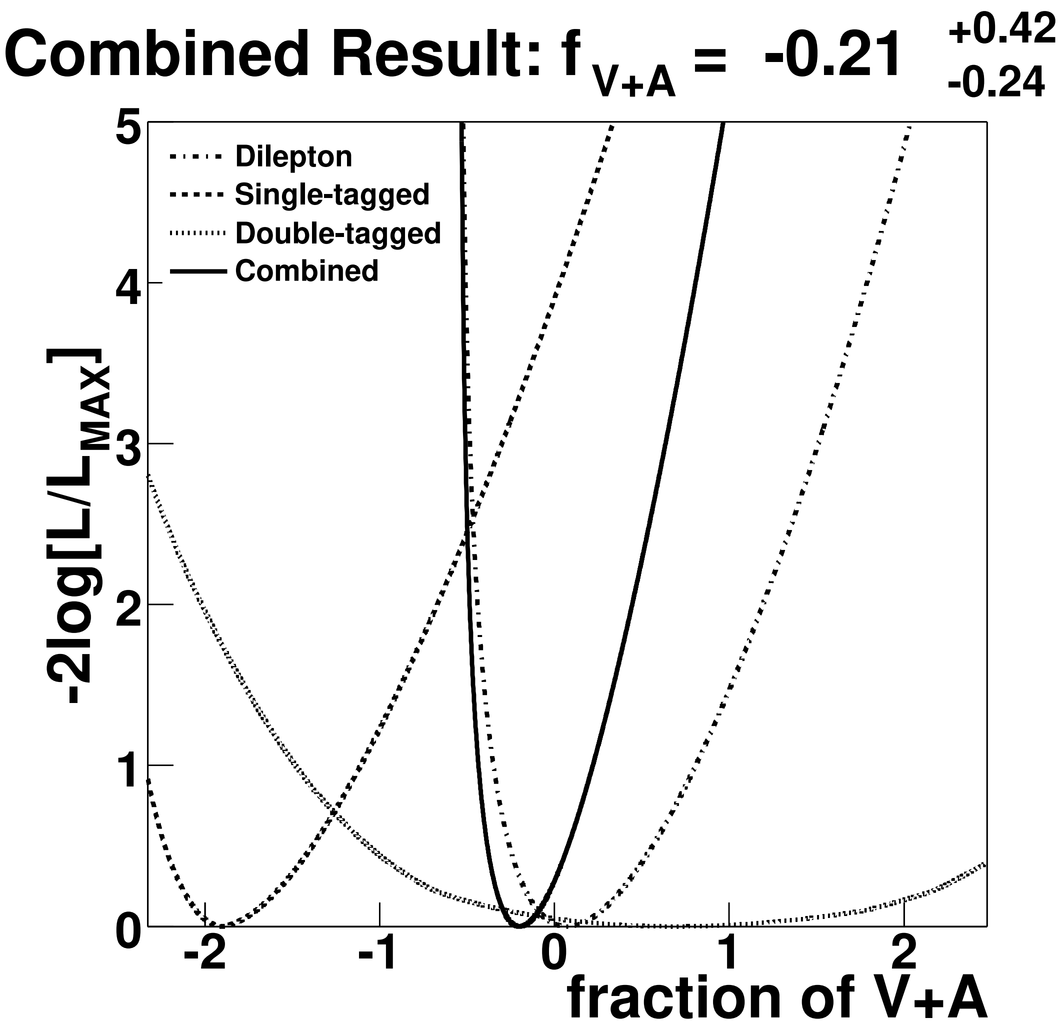

Figure 3: $-2\log\mathcal{L}$ as a function of f_{V+A} for all samples and for the combined likelihood fit. The result for the dilepton sample is $f_{V+A} = 0.08^{+0.74}_{-.0.42}$, for the single-tagged sample is $f_{V+A} =$ -1.91$^{+0.69}_{-.0.48}$, and for the double-tagged sample is $f_{V+A} = 0.63^{+2.62}_{-2.11}$. Errors are statistical only.

bined result is inconsistent with a pure V+A theory at a confidence level equivalent to the probability of a 2.7σ Gaussian statistical fluctation.

In conclusion, we have used the measurement of $M_{\ell b}$ in $t\bar{t}$ events to measure the polarization of W bosons in top decay. The results are consistent with the V$-$A theory of the weak interaction. The data are used to set a limit on the fraction of top decays mediated by a V+A interaction. This is the first result providing significant direct evidence against a pure V+A theory of weak interactions in top decay; it also provides the first significant limits on partial admixtures of a V+A interaction with the expected V$-$A reaction.

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