Search for V+A Current in Top Quark Decay in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report an upper limit on the fraction of $V+A$ current, f_{V+A}, in top quark decays, using approximately 700 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.96 TeV acquired by the upgraded Collider Detector at Fermilab. For the decay $t \to Wb \to \ell\nu b$ (where $\ell = e$ or μ), the invariant mass of the charged lepton and the bottom quark jet is sensitive to the polarization of the W boson. We determine $f_{V+A} = -0.06 \pm 0.25$ given a top quark mass of 175 GeV/c^2. We set an upper limit on f_{V+A} of 0.29 at the 95% confidence level, which represents an improvement by a factor of two on the previous best direct limit.

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The decay of the top quark, the most massive fundamental particle observed by experiment [1, 2], is particularly interesting as a direct probe of the charged current weak interaction at the highest energy scale presently available. In the standard model, the spin-$\frac{1}{2}$ top quark decays via the charged current weak interaction to a spin-1 W^+ boson and a spin-$\frac{1}{2}$ b quark [3], with a branching fraction above 99% and width $\Gamma_t = 1.4$ GeV [4] for a top mass of 175 GeV/c^2. The lifetime of the top quark, $\hbar/\Gamma_t \sim 5 \times 10^{-25}$ s, is an order of magnitude shorter than the typical strong interaction time-scale for binding of quarks into hadrons, $\hbar/\Lambda_{QCD} \sim 3 \times 10^{-24}$ s. Therefore, the top quark decays before hadronization, and the spin information is directly transferred to the decay products. In the limit $m_b \to 0$, the pure $V-A$ theory of the weak interaction predicts that the b quark has left-handed $(-1/2)$ polarization (helicity) and the W^+ boson can only have either longitudinal (zero) or left-handed

(-1) polarization. The right-handed ($+1$) polarization is forbidden. The fraction f^0 of W^+ bosons with longitudinal polarization is predicted at leading order in perturbation theory to be $f^0 = m_t^2/(2m_W^2 + m_t^2) = 0.70$ [5]. The non-zero b quark mass and the higher-order QCD and electroweak radiative corrections modify these predictions below the 1% level [6, 7]. However, the presence of non-standard-model couplings in the tWb vertex could significantly modify the polarization of the top quark decay products [5, 8–10]. Previous results have either been limited by the small statistics of the top quark samples [11–14] or have only set indirect limits [15].

In this Letter, we search for a $V{+}A$ current in top quark decay, while assuming that the $t\bar{t}$ production mechanism is in agreement with the standard model prediction. We further assume the absence of couplings from magnetic moment interactions in the tWb interaction, so that f^0 is unchanged from 0.70 [5]. Then, the $V+A$ fraction f_{V+A} is related to the fraction f^+ of right-handed W^+ bosons by $f_{V+A} = f^+/(1-f^0)$, and the $V-A$ fraction $f_{V-A} \equiv 1 - f_{V+A}$ is related to the fraction f^- of left-handed W^+ bosons by $f_{V-A} = f^-/(1-f^0)$. The W^+ boson polarization can be inferred from the angular distribution of the charged lepton [16] in the decay $W^+ \to \ell^+\nu$,

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{4}(1-\cos^2\theta)f^0 + \frac{3}{8}(1-\cos\theta)^2 f^- + \frac{3}{8}(1+\cos\theta)^2 f^+,$$

where the angle θ is the polar angle 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. We use the observable $M_{\ell b}^2$, the square of the invariant mass of the charged lepton and the jet from the b quark, which is related to $\cos\theta$ by

$$M_{\ell b}^2 \simeq \frac{1}{2}(m_t^2 - m_W^2)(1+\cos\theta).$$

The relation is exact in the limit $m_b \to 0$.

This search is based on a data set with an integrated luminosity of approximately 700 pb^{-1} acquired by the Collider Detector at Fermilab (CDF II)[17] from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. A 96-layer outer drift chamber [18] reconstructs the trajectories of charged particles and measures their momenta in the region $|\eta| < 1$ [19]. An eight-layer silicon microstrip detector [20] provides precision tracking information in the region $|\eta| < 2$ to identify displaced vertices associated with b hadron decays. The entire tracking volume is located inside a 1.4 T magnetic field. Electromagnetic and hadronic calorimeters measure the energies of particle showers. Drift chambers and scintillation counters provide muon identification outside the calorimeters. Gas Cherenkov counters [21] determine the luminosity. The data are collected with an inclusive lepton trigger that requires an electron (muon) with $|\eta| < 1$ and $E_T > 18$ GeV ($P_T > 18$ GeV/c) [19].

We study three independent data samples enriched in $t\bar{t}$ events. Two of the data samples are in the lepton+jets channel, with $t\bar{t} \to W^+bW^-\bar{b}$ events where one of the W bosons decays hadronically and the other leptonically. The lepton+jets event selection requires one isolated lepton with $E_T > 20$ GeV, $\not\!\!E_T > 20$ GeV [19], at least three jets with $E_T > 15$ GeV, and one or two b-tagged jets. More details on the selection, the b-tagging procedure, and the sample composition can be found in Ref. [22]. We model the hard $t\bar{t}$ process with the Monte Carlo (MC) event generator ALPGEN [23] with CTEQ5L [24] parton densities and PYTHIA [25] for hadronization, under the assumption that the top quark mass is 175 GeV/c^2. We simulate the detector response using GEANT [26, 27]. For $t\bar{t}$ production with $V-A$ top quark decay, we estimate a selection efficiency, including the branching fraction, of $\mathcal{A}_{V-A} = 3.4\%(1.2\%)$ for events with one (two) b-tagged jets. Due to the lower average p_T of the charged lepton for $V-A$, this is a factor 0.92 below the efficiency for $V+A$.

For the lepton+jets sample with a single b-tagged jet, the b-tagged jet is from the same top quark decay as the charged lepton in approximately half of the $t\bar{t}$ events. The background $M_{\ell b}^2$ distribution is a combination of 85% W+jets, modeled by ALPGEN $Wb\bar{b}$, and 15% multi-jet events, modeled by non-isolated lepton+jets data events. Background-dominated data samples with only one jet or only two jets are consistent, in terms of both the rate and the shape of the $M_{\ell b}^2$ distribution, with our model of the background. In 695 pb^{-1}, we observe 304 candidates with a total expected background of 88±11 events.

For the lepton+jets sample with two b-tagged jets, the two possible $M_{\ell b}^2$ values of the charged lepton with either the highest or the second highest E_T b-tagged jet are used to construct a 2-D distribution. In this way, we keep both the correct and incorrect combinations, and account for their correlation. The background is modeled by ALPGEN $Wb\bar{b}$; here the multi-jet background is negligible. Non-uniform binning was applied in the 2-D $M_{\ell b}^2$ distributions in order to ensure sufficient MC events in each bin. In 695 pb^{-1}, we find 75 candidates with a total expected background of 9±2 events.

The third sample is in the dilepton channel, with $t\bar{t} \to W^+bW^-\bar{b}$ events where both W bosons decay leptonically. The dilepton event selection requires two identified leptons with opposite electric charge and $E_T > 20$ GeV, $\not\!\!E_T > 25$ GeV, and at least two jets with $E_T > 15$ GeV. More details on the selection and the sample composition can be found in Ref. [28]. For $t\bar{t}$ production with $V-A$ top quark decay, modeled by ALPGEN as described above, we estimate a selection efficiency, including the branching fraction, of $\mathcal{A}_{V-A} = 0.72\%$, a factor 0.88 below the efficiency for $V+A$. The two possible $M_{\ell b}^2$ values for a charged lepton with either the highest or the second highest E_T jet, assumed to be produced by the fragmentation of the b quarks, are used to construct a 2-D distribution.

As we can reconstruct $M_{\ell b}^2$ from the top quark decay and from the anti-top quark decay, we make one entry for each charged lepton. The effect of the correlation between the spins of the top quark and the anti-top quark is negligible here. Again, non-uniform binning in the 2-D $M_{\ell b}^2$ distributions is applied. The background $M_{\ell b}^2$ distribution is the combination of three background types: approximately 50% from $Z/\gamma^* \to \ell^+\ell^-$ with associated jets, 30% from $W \to \ell\nu$ with associated jets where a jet is misidentified as a lepton, and 20% from massive diboson pairs, WW/WZ. The Z/γ^* and diboson background $M_{\ell b}^2$ distributions are modeled by ALPGEN. The misidentified lepton background is based on inclusive lepton trigger data where the second lepton is instead a jet (charged particle track) weighted by a probability for misidentification as an electron (muon). A background-dominated data sample with only one jet is consistent, in terms of both the rate and the shape of the $M_{\ell b}^2$ distribution, with our model of the background. In 750 pb^{-1}, we observe 64 candidates (12 ee, 24 $\mu\mu$, and 28 $e\mu$) with a total estimated background of 20±4 events.

The fraction f_{V+A} is estimated by comparing the $M_{\ell b}^2$ distribution in data with parent $M_{\ell b}^2$ distributions for $t\bar{t}$ production with $V-A$ top quark decay ($f_{V+A} = 0.0$), $t\bar{t}$ production with $V+A$ top quark decay ($f_{V+A} = 1.0$), and backgrounds. A binned log likelihood fit procedure is used to extract the parameter of interest, f_{V+A}. We represent the imperfectly known accepted background cross section for each sample, σ_{bg}, and the $t\bar{t}$ cross section [29, 30], $\sigma_{t\bar{t}}$, by nuisance parameters. The analytic expression for the likelihood for each sample,

$$\mathcal{L} = \Big[\prod_{i=0}^{N} P(n_i,\mu_i)\Big] \times G(\sigma_{bg},\delta_{\sigma_{bg}}) \times G(\sigma_{t\bar{t}},\delta_{\sigma_{t\bar{t}}}), \quad (1)$$

is the product over all N bins in $M_{\ell b}^2$ of the Poisson probabilities of observing n_i entries in a given bin i, where the average expected bin content is μ_i, and the Gaussian constraints on the estimated background and the predicted $t\bar{t}$ production cross sections, as shown in Table I. The μ_i are given by:

$$\mu_i = N^{data}\Big[x_{V+A}\hat{T}^i_{V+A} + x_{V-A}\hat{T}^i_{V-A} + x_{bg}\hat{T}^i_{bg}\Big], \quad (2)$$

$$x_{V+A} = \frac{f_{V+A}\mathcal{A}_{V+A}\sigma_{t\bar{t}}}{\sigma_{bg} + \sigma_{t\bar{t}}[\mathcal{A}_{V+A}f_{V+A} + \mathcal{A}_{V-A}(1-f_{V+A})]}, \quad (3)$$

$$x_{V-A} = \frac{(1-f_{V+A})\mathcal{A}_{V-A}\sigma_{t\bar{t}}}{\sigma_{bg} + \sigma_{t\bar{t}}[\mathcal{A}_{V+A}f_{V+A} + \mathcal{A}_{V-A}(1-f_{V+A})]}, \quad (4)$$

$$x_{bg} = \frac{\sigma_{bg}}{\sigma_{bg} + \sigma_{t\bar{t}}[\mathcal{A}_{V+A}f_{V+A} + \mathcal{A}_{V-A}(1-f_{V+A})]}. \quad (5)$$

Here, N^{data} is the total number of observed events for the sample. The x_{V+A}, x_{V-A}, and x_{bg} are the fractions of $t\bar{t}$ production with V+A top quark decay, $t\bar{t}$ production with V−A top quark decay, and background, respectively. The $\hat{T}^i_{V+A}$, $\hat{T}^i_{V-A}$, and $\hat{T}^i_{bg}$ are the probabilities for an event to occupy bin i of the corresponding $M_{\ell b}^2$ distribution. Note that $\sum_i \hat{T}^i = 1.0$. The combined likelihood is the product of the likelihoods of the three samples, but with one common Gaussian constraint on the $t\bar{t}$ cross section.

TABLE I: The input values for the nuisance parameters, and the values from the best fit to the combined samples.

Nuisance parameter	Input (pb)	Fit (pb)
$\sigma_{t\bar{t}}$	6.7 ± 1.0	7.3 ± 0.9
$\sigma_{\rm bg}$ lepton+jets 1 b-tag	0.156 ± 0.017	0.154 ± 0.016
$\sigma_{\rm bg}$ lepton+jets 2 b-tag	0.013 ± 0.002	0.013 ± 0.002
$\sigma_{\rm bg}$ dilepton	0.026 ± 0.006	0.022 ± 0.006

The robustness of the fitting procedure has been tested with MC simulated experiments. For a given experiment and a particular sample, the number of observed data events is distributed in three categories ($t\bar{t}$ production with $V+A$ top quark decay, $t\bar{t}$ production with $V-A$ top quark decay, and background) according to their expected fractions from Equations 3-5. For each category, the events are generated from the relevant $M_{\ell b}^2$ parent distribution. The hypotheses that $f_{V+A} = 0.0, 0.1, \ldots, 1.0$ are studied for 2000 experiments for all samples combined, as well for the three samples separately. In all cases, the fit is unbiased and stable. An expected statistical uncertainty of 0.22 on f_{V+A} is found for the combined case, while for the separate samples we found 0.35 for lepton+jets events with one b-tagged jet, 0.41 for lepton+jets events with two b-tagged jets, 0.27 for all lepton+jets events, and 0.46 for dilepton events. In all cases, this uncertainty includes a small component ($\lesssim 0.02$) due to the uncertainties on the background and $t\bar{t}$ cross sections.

The maximum likelihood fit to the lepton+jets sample yields a value of $f_{V+A} = 0.21 \pm 0.28$, with $f_{V+A} = 0.16 \pm 0.36$ for the subset of events with one b-tagged jet and $f_{V+A} = 0.28 \pm 0.44$ for the subset of events with two b-tagged jets. For the dilepton sample, we obtain $f_{V+A} = -0.64 \pm 0.37$. The probability to obtain a value smaller than the dilepton result is 10% for the hypothesis $f_{V+A} = 0$. The lepton+jets and dilepton results are compatible at about 1.8 standard deviations.

The estimates of the systematic uncertainties on the measured value for f_{V+A} are shown in Table II for all samples combined. The leading sources of systematic uncertainty arise from uncertainties on the measured jet energy [31], the background shape and normalization, and limited MC statistics. We determine all systematic uncertainties by performing MC simulated experiments in which the systematic parameter in question is varied and the resulting simulated data are fit to the default parent distributions. All systematic uncertainties are evaluated

TABLE II: The systematic uncertainties on the measurement of f_{V+A} for all samples combined.

Source	Uncertainty
Jet energy	0.10
Background modeling	0.04
MC statistics	0.04
Initial/Final state QCD radiation	0.02
Multiple $p\bar{p}$ interactions	0.02
b-tag efficiency(E_T)	0.02
MC generator	0.01
Parton densities	0.01
Total	0.12

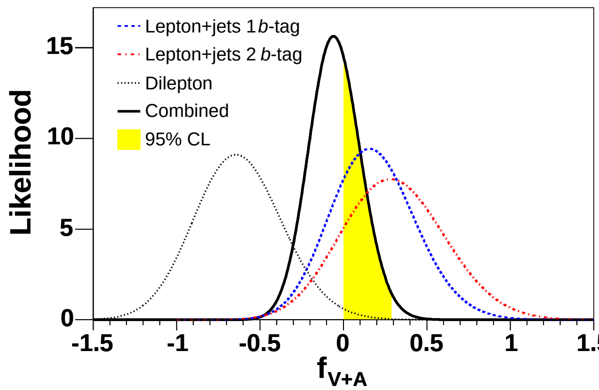

FIG. 1: Likelihood distribution (see Equation 1) for the lepton+jets and dilepton data samples separately and combined.

at $f_{V+A} = 0$; we find the dominant uncertainty is insensitive to the value of f_{V+A}.

Many of the above sources of systematic uncertainty also contribute significantly to the systematic uncertainty on the measurement of the top quark mass [32]. We choose to quote our result at a top quark mass value of 175 GeV/c^2, where the dependence of the measurement (upper limit) for f_{V+A} is ± 0.07 (± 0.06) for a ∓ 2 GeV/c^2 shift in top quark mass.

Combining all samples, the result for the fraction of $V+A$ current in top quark decay is

$$f_{V+A} = -0.06 \pm 0.22 \text{ (stat.)} \pm 0.12 \text{ (syst.)}.$$

This value is in agreement with the standard model. Table I summarizes the fitted values for the nuisance parameters. The likelihood distribution is shown in Fig. 1 for the combined sample as well as for each individual sample. The good agreement in the $M^2_{\ell b}$ distribution between data and the best fit result for f_{V+A} from the combined sample is shown in Figs. 2, 3, and 4, where the highest bins also contain overflow entries. For comparison, $f_{V+A} = 1.00$ is also shown.

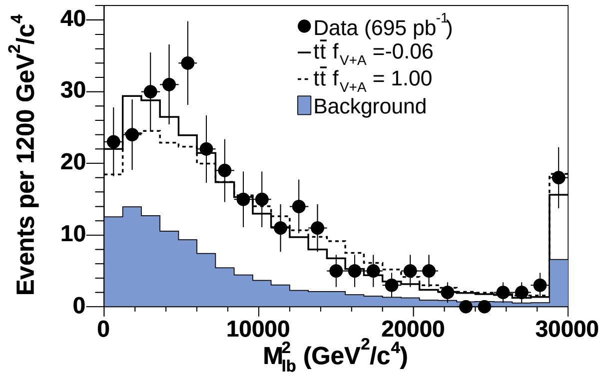

FIG. 2: The $M^2_{\ell b}$ distribution for the lepton+jets sample with a single b-tagged jet. For $f_{V+A} = -0.06$, the χ^2 probability is 69%.

In the absence of a signal, we evaluate an upper limit on f_{V+A} using a Bayesian approach. The profile likelihood function is first determined as a function of f_{V+A}, multiplied by a prior flat between 0.0 and 1.0, and normalized to yield the posterior distribution for f_{V+A}. The upper limit at 95% confidence level (CL) is formed by integrating the posterior from zero to the value of f_{V+A} that yields 0.95 for the integral. We verified that this approach yields proper frequentist coverage for $f_{V+A} \leq 0.3$; a small correction, derived by the Neyman construction, would be applied to any upper limit greater than 0.3 to restore coverage in the region $f_{V+A} > 0.3$. From MC simulated experiments for the standard model case where $f_{V+A} = 0$, the median upper limit is 0.38 and 68% of experiments set an upper limit between 0.2 and 0.6.

Combining all samples, we set an upper limit on the fraction of $V+A$ current in top quark decay of

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

This is an improvement by a factor of two on the previous best direct limit [11]. Converting the results for f_{V+A} to the fraction of right-handed W^+ bosons, we obtain $f^+ = -0.02 \pm 0.07$ (stat.) ± 0.04 (syst.) and $f^+ < 0.09$ at 95% CL.

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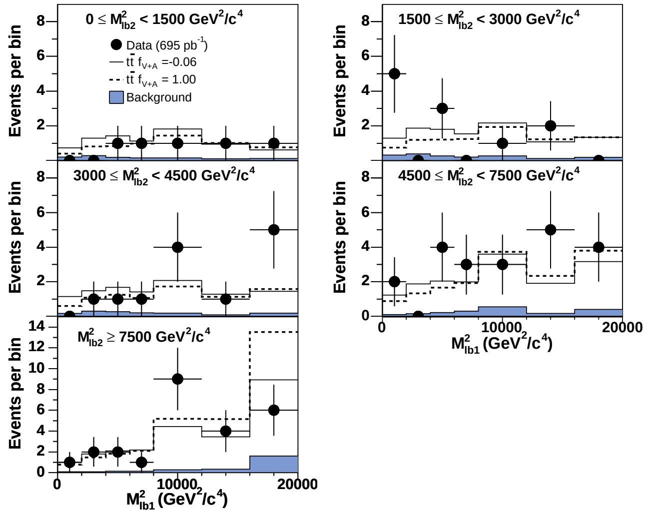

FIG. 3: The invariant mass squared of the charged lepton and the highest E_T b-tagged jet, $M^2_{\ell b1}$, in five regions of the invariant mass squared of the charged lepton and the second highest E_T b-tagged jet, $M^2_{\ell b2}$, for the lepton+jets sample with two b-tagged jets. For $f_{V+A} = -0.06$, the χ^2 probabilities are 92%, 3%, 10%, 18%, and 47% in order of increasing $M^2_{\ell b2}$.

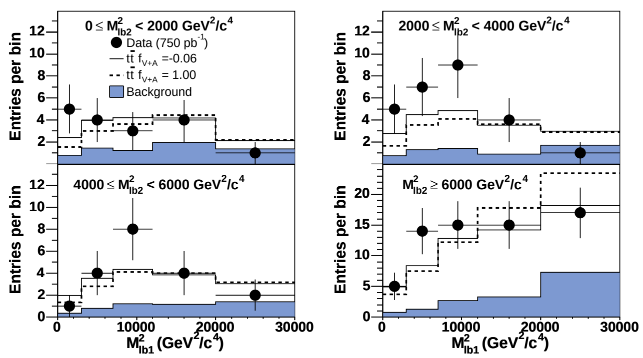

FIG. 4: The invariant mass squared of a charged lepton and the highest E_T jet, $M^2_{\ell b1}$, in four regions of the invariant mass squared of the charged lepton and the second highest E_T jet, $M^2_{\ell b2}$, for the dilepton sample. There are two entries per event, one for each lepton. For $f_{V+A} = -0.06$, the χ^2 probabilities are 58%, 14%, 54%, and 51% in order of increasing $M^2_{\ell b2}$.

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[1] F. Abe et al. (CDF Collaboration), Phys. Rev. Lett. **74**, 2626 (1995).
[2] S. Abachi et al. (DØ Collaboration), Phys. Rev. Lett. **74**, 2632 (1995).
[3] Charge conjugate decays, with replacement of left-handed by right-handed polarization, are implicit.
[4] M. Jezabek and J. H. Kuhn, Nucl. Phys. B **314**, 1 (1989).
[5] G. L. Kane, G. A. Ladinsky, and C. P. Yuan, Phys. Rev. D **45**, 124 (1992).
[6] M. Fischer, S. Groote, J. G. Korner, and M. C. Mauser, Phys. Rev. D **63**, 031501(R) (2001).
[7] H. S. Do, S. Groote, J. G. Korner, and M. C. Mauser, Phys. Rev. D **67**, 091501(R) (2003).
[8] M. A. B. Beg, R. V. Budny, R. Mohapatra, and A. Sirlin, Phys. Rev. Lett. **38**, 1252 (1977).
[9] G. Triantaphyllou, J. Phys. G **26**, 99 (2000).
[10] D. Choudhury, T. M. P. Tait, and C. E. M. Wagner, Phys. Rev. D **65**, 053002 (2002).
[11] D. Acosta et al. (CDF Collaboration), Phys. Rev. D **71**, 031101(R) (2005).
[12] A. Abulencia et al. (CDF Collaboration), Phys. Rev. D **73**, 111103(R) (2006).
[13] V.M. Abazov et al. (DØ Collaboration), Phys. Lett. B **617**, 1 (2005).
[14] V.M. Abazov et al. (DØ Collaboration), Phys. Rev. D **72**, 011104(R) (2005).
[15] F. Larios, M. A. Perez, and C. P. Yuan, Phys. Lett. B **457**, 334 (1999).
[16] We use lepton to denote an electron or a muon.
[17] D. Acosta et al. (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).
[18] A. Affolder et al., Nucl. Instrum. Methods A **526**, 249 (2004).
[19] We use a cylindrical coordinate system where the z axis is along the proton beam direction and θ is the polar angle. Pseudorapidity is $\eta = -\ln\tan(\theta/2)$, while transverse momentum is $p_T = |p|\sin\theta$, and transverse energy is $E_T = E\sin\theta$. Missing transverse energy, $\not\!\!E_T$, is defined as the magnitude of $-\sum_i E^i_T \hat{n}_i$, where $\hat{n}_i$ is the unit vector in the azimuthal plane that points from the beam line to the i^{th} calorimeter tower.
[20] A. Sill, Nucl. Instrum. Methods A **447**, 1 (2000).
[21] D. Acosta et al., Nucl. Instrum. Methods A **494**, 57 (2002).
[22] D. Acosta et al. (CDF Collaboration), Phys. Rev. D **71**, 052003 (2005).
[23] M. L. Mangano et al., J. High Energy Phys. **0307**, 001 (2003).
[24] H. L. Lai et al. (CTEQ Collaboration), Eur. Phys. J. C **12**, 375 (2000).
[25] T. Sjostrand et al., Comput. Phys. Commun. **135**, 238 (2001).
[26] E. Gerchtein and M. Paulini, eConf **C0303241**, TUMT005 (2003).
[27] R. Brun et al., CERN-DD/EE/84-1 (1987).
[28] D. Acosta et al. (CDF Collaboration), Phys. Rev. Lett. **93**, 142001 (2004).
[29] M. Cacciari et al., J. High Energy Phys. **404**, 68 (2004).
[30] N. Kidonakis and R. Vogt, Phys. Rev. D **68**, 114014 (2003).
[31] A. Bhatti et al., Nucl. Instrum. Methods A **566**, 375 (2006).
[32] W. M. Yao et al., J. Phys. G **33**, 1 (2006).