Measurement of the W Helicity in Top Quark Decays

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We present a measurement of the helicity of the $W$-boson in top quark events using $t\bar{t}$ decays in the $e$+jets and $\mu$+jets final states.

This is version 2.3 of the note.

Preliminary Results for Summer 2004 Conferences
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I. INTRODUCTION

One test of the standard model (SM) is the measurement of the helicity of $W$-bosons in top quark decays. In the SM, the top quark decays via the V-A charged current interaction. At the Born level, this parity violating interaction limits decays of top quarks into $W$’s with longitudinal and left-handed helicity states with fractions $f^0$ and $f^-$ respectively. Higher order corrections are expected to be 1-2% [1]. The branching ratio for $f^0$ is a function of the top quark mass ($m_t$) $W$-boson mass ($M_W$), and $b$-quark mass [1]:

$$\frac{f^0}{f^-} = \frac{(1 - y^2)^2 - x^2(1 - 2x^2 + y^2)}{(1 - y^2)^2 + x^2(1 - 2x^2 + y^2)}$$  \hspace{1cm} (1)

where $x = M_W/m_t$ and $y = m_b/m_t$. The effects of the $b$-quark mass are small and hence:

$$f^0 = \frac{m_t^2}{m_t^2 + 2M_W^2}$$  \hspace{1cm} (2)

With the present measured values of the top quark and $W$-boson mass the SM prediction gives $f^0 \approx 0.70$ and $f^- \approx 0.30$. There are no decays into right-handed $W$ helicity states ($f^+ = 0.0$) since the $b$–quark helicity in this case would necessarily be right-handed and hence greatly suppressed. The helicity states for antitop decays would be reversed from that given above. An early theoretical treatment of top quark decays is given in [2]. In this measurement we search for a non-zero value of $f^+$ that would be evidence for a possible V+A admixture to the $t \to b$ current.

In Run I of the Tevatron, CDF measured $f^+ = 0.11 \pm 0.15$ and $f^0 = 0.91 \pm 0.37 \pm 0.13$ [3]. DØ obtained $f^0 = 0.56 \pm 0.31$ [4][5]. In addition to direct measurements, data on $b \to s\gamma$ decays have been used to set a limit on $W_R$ and $W_L$ mixing [6],[7].

Our analysis consists of selecting events using nearly the same criteria used by the Winter 2004 lepton-jets $t\bar{t}$ production cross section analyses. One exception is that we do not reject events that contain jets that are tagged with soft muons. In addition we also employ topological criteria to increase the expected number of signal versus background.

For events passing all selection criteria we perform a kinematic fit using the HITFIT package to select the $b$-jet associated with the leptonic $W$. We use the term “leptonic $W$” as shorthand notation for the phrase “$W$ that decays leptonically”. In the very small percentage of cases where the kinematic fit does not converge, we use a simpler $\chi^2$ method to select the $b$-jet associated with the leptonic $W$. Both methods use the measured top mass and $W$-boson mass as constraints.

Once the $b$-jet associated with the leptonic $W$ is identified we calculate $\cos\theta^*$. We define $\cos\theta^*$ as the cosine of the angle between the lepton momentum and the initial $W$-boson momentum when boosted to the rest frame of the leptonic $W$. With this definition, the $\cos\theta^*$ distribution for right-handed $W$’s is peaked towards $\cos\theta^* = +1$. We use the object momenta returned from the kinematic fit in calculating $\cos\theta^*$.

We produce templates in $\cos\theta^*$ for $t\bar{t}$ signal assuming different V+A fractions $f^+$ and for $Wjjjjj$ and “QCD” backgrounds. We rely on Monte Carlo to produce the different $\cos\theta^*$ distributions except for the multijet background (called “QCD”), which is taken from data.

We use these templates in a binned likelihood fit to find the V+A fraction $f^+$ given by the data. The resulting log likelihood curves are interpreted using both Bayesian and frequentist approaches. We also use these templates in fits to ensembles of Monte Carlo events in order to test the veracity of our procedure and to estimate systematic uncertainties.
II. EVENT SELECTION

Our data samples consist of ROOT-tuples from the MUQCD and EMQCD skims processed with the Nefertiitii version of top_analyze. The data runs analyzed make use of the file lists muqcd-skim-nefertiti-030904.dat and emqcd-skim-final-030404.dat found in /rooms/depot/johns/cvs/dimu/p14_lists on the CLUEDØ cluster. Data from bad luminosity blocks are rejected using the top_dq package. The integrated luminosity of the surviving $\mu$+jets data is 158.4 pb$^{-1}$ and that of the $e$+jets data is 168.7 pb$^{-1}$.

The Monte Carlo samples consist of events generated by ALPGEN or PYTHIA. All Monte Carlo events were processed through GEANT, DØRECO, and top_analyze. The standard $t\bar{t}$ sample corresponds to the Top group’s Tune A version. The standard $Wjjjj$ sample corresponds to the Higgs group’s Tune A version. In order to test the hypothesis of a non-zero $f^+$ fraction, we also used ALPGEN samples which varied the $P_Q$ coupling in increments from purely $P_Q^+$ to purely $P_Q^-$, resulting in $f^+$ varying from 0.0 to 0.3. (The fraction of decays into longitudinal $W$’s is $f^0 = 0.7$ for both $V - A$ and $V + A$ couplings, so $f^0$ does not change in any of our Monte Carlo samples.) We call these samples the $f^+$ samples. The $f^+$ samples corresponded to the Top group’s Tune A version.

These are the default signal and background samples used in this analysis unless otherwise stated. To study the systematic uncertainty associated with these Monte Carlo samples we used alternative samples to model signal and background. We used events generated by PYTHIA as an alternative signal sample and events generated by ALPGEN iqopt10 version as an alternative background sample.

Additional information on the data and Monte Carlo samples used can be found in the DØNote that contains general documentation (data sets, triggers, reconstruction, etc.) for top analyses carried out in 2004 [8]. A brief summary of relevant parameters for Monte Carlo generation is given in Table I.

We require events to have fired the correct lepton+jets L1, L2, and L3 triggers. To do this we employ the top_dq package v00-04-00. We simulate these triggers for Monte Carlo events using the top_trigger package v00-20-03.

Our preselection criteria for the $\mu + jets$ channel are given in Table II. These criteria are identical to those used in the $t\bar{t}$ production cross section analysis for Winter 2004 conferences, except we do not reject events in which a soft muon is associated with a jet (i.e. we have no SLV veto).

Many of the variable definitions can be found in [8] and [9]. Isolated muons are defined by Rat11<0.08 and RatTrk<0.06. Rat11 is the sum of the $E_T$ of calorimeter clusters in a hollow cone between $\Delta R=0.1$ and $\Delta R=0.04$ divided by the $p_T$ of the muon. RatTrk is the sum of the $p_T$ of all tracks within a cone of radius $\Delta R=0.5$ divided by the $p_T$ of the muon. The $\Delta \phi(\mu, E_T)$ triangle cut is defined as

- $\Delta \phi(\mu, E_T) > 1.2 - E_T[GeV] \times 1.2/38$
- $\Delta \phi(\mu, E_T) < 1.3 + E_T[GeV] \times (\pi - 1.3)/24$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Top Tune A</th>
<th>Higgs Tune A</th>
<th>Higgs iqopt10</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF</td>
<td>CTEQ6.1M</td>
<td>CTEQ5L</td>
<td>CTEQ5L</td>
</tr>
<tr>
<td>$Q^2$</td>
<td>$(M_W/2)^2$</td>
<td>$M_W^2 + \sum p_T^2$</td>
<td>$&lt; p_T^2 &gt;$</td>
</tr>
<tr>
<td>Underlying event</td>
<td>Tune A</td>
<td>Tune A</td>
<td>Tune A</td>
</tr>
<tr>
<td>$p_T^{\text{parton}}$</td>
<td>&gt; 12 GeV</td>
<td>&gt; 8 GeV</td>
<td>&gt; 8 GeV</td>
</tr>
<tr>
<td>$</td>
<td>p_T^{\text{parton}}</td>
<td>$</td>
<td>&lt; 2.7</td>
</tr>
</tbody>
</table>

TABLE I: Generation parameters associated with Monte Carlo samples used in this analysis
TABLE II: Preselection criteria for the $\mu$+jets channel

<table>
<thead>
<tr>
<th>Cut</th>
<th>Selection Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\geq 3$ tracks at the vertex</td>
</tr>
<tr>
<td>2</td>
<td>$</td>
</tr>
<tr>
<td>3</td>
<td>$\geq 1\mu$</td>
</tr>
<tr>
<td>4</td>
<td>Only 1 isolated $\mu$</td>
</tr>
<tr>
<td>5</td>
<td>Highest $P_T^\mu &gt; 20\text{ GeV}$</td>
</tr>
<tr>
<td>6</td>
<td>$</td>
</tr>
<tr>
<td>7</td>
<td>$</td>
</tr>
<tr>
<td>8</td>
<td>$\geq 4$ jets</td>
</tr>
<tr>
<td>9</td>
<td>4 jets with $P_T &gt; 15\text{ GeV}$</td>
</tr>
<tr>
<td>10</td>
<td>$\Delta R(\mu, \text{jet}) &gt; 0.5$</td>
</tr>
<tr>
<td>11</td>
<td>$E_T &gt; 17\text{ GeV}$</td>
</tr>
<tr>
<td>12</td>
<td>$\Delta \phi(\mu, E_T)$ triangle cut</td>
</tr>
<tr>
<td>13</td>
<td>$\mu$+jets trigger requirement</td>
</tr>
<tr>
<td>14</td>
<td>Isolated $\mu$ is the highest $P_T$ $\mu$</td>
</tr>
</tbody>
</table>

TABLE III: Preselection criteria for the $e$+jets channel

- $\Delta \phi(\text{leading jet}, E_T) < 2.2 + E_T[\text{GeV}] \ast (\pi - 2.2)/26$

Our preselection criteria for the $e$+jets channel are given in Table III. These criteria are identical to those used in the $t\bar{t}$ production cross section analysis for Winter 2004 conferences, except we do not reject events in which a soft muon is associated with a jet (i.e. we have no SLV veto).

Many of the variable definitions can be found in [8] and [9]. The EM likelihood is used to separate good electrons from background. The likelihood is based on seven variables listed, but not defined, here: $f_{\text{em}}, X_c^2, \frac{\text{frac}E_T^{\text{cal}}}{p_{\text{trk}}}, p_{\text{trk}}, \text{Prob}(X_{\text{spatial EM}}^2 - \text{trk})$, DCA to primary vertex, number of tracks in a cone of radius $\Delta R=0.05$, and the sum of the $p_T$ of all tracks in a cone of radius $\Delta R=0.04$. The $\Delta \phi(e, E_T)$ cut is defined as:

- $\Delta \phi(e, E_T) > 1.7 - 1.7 \ast E_T/80[\text{GeV}]$

Our final selection criteria are the preselection criteria plus a topological criterion used to further increase the expected ratio of $S/\sqrt{S + B}$. Presently we use a cut on a six-variable topological likelihood $L_t$ given in Table IV. The topological likelihood variables and cut value were optimized by performing ensemble tests and choosing a definition and cut that minimized the average width of the 68% Bayesian confidence interval for the measurement of $f^+$. The three choices of likelihood tried and the optimization procedure is
The topological likelihood \( L_t \) (which we call choice 2) is based on six kinematic variables, defined as follows:

- **Aplanarity \( \mathcal{A} \)**, defined as \( 3/2 \) times the smallest eigenvalue of the normalized momentum tensor of the jets and lepton. \( \mathcal{A} \) is a measure of the deviation from flatness of the event, and \( t\bar{t} \) events tend to have larger values than background events.

- **\( H_{T2}^{l} \)**, defined as the sum of the \( E_T \)'s of all the jets in the event except the highest-\( E_T \) one, divided by the sum of the magnitudes of the longitudinal momenta of the jets, lepton, and neutrino (\( p_z \) of the neutrino is calculated using a \( W \) mass constraint). Top quark events will tend to be more central and thus have higher values of \( H_{T2}^{l} \).

- **\( K_{T_{\text{min}}}^{c} \)**, defined as the distance in \( \eta - \phi \) space between the closest pair of jets multiplied by the \( E_T \) of the lowest-\( E_T \) jet in the pair, and divided by the \( E_T \) of the \( W \). Only the four leading-\( E_T \) jets are considered in computing this variable. Jets arising from gluon radiation (as is the case for background) will tend to result in low values of \( K_{T_{\text{min}}}^{c} \).

- **Sphericity \( S \)** is defined as \( 3/2 \) times the sum of the two smallest eigenvalues of the normalized momentum tensor of the jets in the event. This variable is similar to \( \mathcal{A} \), and \( t\bar{t} \) events will tend to have larger values than background.

- **\( H_T \)**, defined as the as the scalar sum of all jet \( P_T \) values > 15 GeV. Jets arising from gluon radiation in general have lower \( P_T \) than jets in \( t\bar{t} \) events so background events will tend to have smaller values of \( H_T \) compared to signal events.

- **HITFIT \( \chi^2 \)**, defined as the \( \chi^2 \) associated with a kinematic fit to the hypothesis of \( t\bar{t} \) decays in the \( e+\text{jets} \) or \( \mu+\text{jets} \) final states. Signal events will naturally have smaller \( \chi^2 \) values than background events. HITFIT is the name of the software package used to perform the kinematic fit.

In our optimization procedure we considered two additional topological likelihoods, which we call choice 1 and choice 3. Choice 1 is a five variable topological likelihood based on the first five kinematic variables itemized above and its origin is historical. Choice 3 is a six variable likelihood based on the kinematic variables aplanarity, sphericity, centrality, \( H_T^{3} \), \( M_{jj}^{\text{min}} \), and HITFIT \( \chi^2 \). Choice 3 is the same one used by [13]. Centrality is defined as \( C = \frac{H_T}{H_E} \) where \( H_E \) is the sum of all jet energies > 15 GeV. It is similar to \( H_T \) but normalized in a way to minimize dependence on the top quark mass. \( H_T^{3} \) is defined as \( H_T - E_{T_{1}}^{\text{jet1}} - E_{T_{2}}^{\text{jet2}} \) where jet 1 and 2 are the highest and second highest \( E_T \) jets in the event. This variable is more sensitive to gluon radiation than \( H_T \) and will tend to result in lower values for background compared to signal. Another variable sensitive to gluon radiation is \( M_{jj}^{\text{min}} \), defined as the minimum dijet mass of all jet pairs.

The four leading jets in \( P_T \) were used to calculate all kinematic variables except \( H_T \) and aplanarity \( \mathcal{A} \). In calculating aplanarity the leading lepton was also used. In calculating \( H_T \) all jets with \( P_T > 15 \text{ GeV/c} \) were used.
Other differences between the three choices of topological likelihoods studied are summarized in Table V.

A final difference between the three choices of topological likelihood is the definition of likelihood used. Let \( s_i \) and \( b_i \) be the signal (\( t\bar{t} \) and background (\( W jjjj \)) probability densities for variable i. Let each event be characterized by a point \( \mathbf{x} \) in the n-dimensional space of the variables.

For choice 1, the likelihood \( L_1 \) is given by:

\[
L_1(\mathbf{x}) = \frac{\prod_{i=1}^{6} s_i(x_i)}{\prod_{i=1}^{5} (s_i(x_i) + b_i(x_i))}
\]

For choices 2 and 3, the likelihood \( L_4 \) is given by:

\[
L_4(\mathbf{x}) = \frac{\exp(\sum_{i=1}^{6} (\ln(s_i(x_i))/\mu_i))}{\exp(\sum_{i=1}^{6} (\ln(s_i(x_i))/\mu_i)) + 1}
\]

The procedure used to select the optimal topological likelihood definition and cut value is itemized below. The procedure uses the full analysis chain that is described in detail in the next sections. The steps used are:

- Generate files of \( \cos \theta^* \) and the values of the three choices of \( L_i \) for Monte Carlo signal and background in the \( \mu+ \)jets and \( e+ \)jets decay channels. For \( t\bar{t} \) signal we use seven samples that vary \( f^+ \) from 0.0 to 0.3.
- Estimate the number of \( t\bar{t}, W jjjj \), and QCD events in the preselected data sample (Table XI).
- For each \( L_i \) choice and cut in increments of 0.05, estimate the number of \( t\bar{t}, W jjjj \), and QCD events in the data (i.e. after the topological likelihood cut).
- For each \( L_i \) choice and cut in increments of 0.05, produce \( \cos \theta^* \) templates for signal and background.
- Estimate the width of the 68\% confidence level for \( f^+ \) by performing ensemble tests using a mock data sample with \( f^+ = 0.15 \).

<table>
<thead>
<tr>
<th>( L_i )</th>
<th>Variable</th>
<th>Probability Density</th>
<th>Probability Density Lookup</th>
</tr>
</thead>
<tbody>
<tr>
<td>choice 1</td>
<td>( S )</td>
<td>( s ) and ( b )</td>
<td>histogram</td>
</tr>
<tr>
<td>choice 2</td>
<td>( \ln(S) )</td>
<td>( s/b )</td>
<td>fit function</td>
</tr>
<tr>
<td>choice 3</td>
<td>( \ln(S) )</td>
<td>( s/b )</td>
<td>fit function</td>
</tr>
</tbody>
</table>

**Table V:** Kinematic variables, variable transformations, probability density and probability density method used in calculating the three choices of topological likelihoods.
TABLE VI: Efficiency of the topological likelihood selection for events that pass the preselection criteria. Where appropriate, the variation with top quark mass and jet energy scale (JES) is noted.

The optimal choice (choice 2) of topological likelihood and cut (Table IV) is that which minimizes the average width of the 68% confidence level for $f^+$ (see Figure 1).

The input signal/background distributions used for choice 2 of the topological likelihood are shown in Figures 2 and 3. The signal and background distributions for each variable listed above are normalized to 1. A polynomial fit to the signal/background distribution is used to calculate $\beta$ for each event.

The efficiency of the topological likelihood cut for preselected signal and background events, and how it varies with jet energy scale and top quark mass, is shown in Table VI. The $t\bar{t}$ samples at $m_t = 175$ GeV are for $f^+ = 0.15$ while $t\bar{t}$ samples at $m_t = 170$ and 180 GeV are for $f^+ = 0.0$.

The efficiency of topological likelihood cut as a function of $f^+$ is shown in Figure 4. There is a slight variation in efficiency that we later account for as an error in the second matrix method. The nominal efficiency we use for $t\bar{t}$ events is taken from the $f^+ = 0.15$ sample.
FIG. 2: Inputs to the topological likelihood (choice 2) for $\mu$+jets $t\bar{t}$ events.
FIG. 3: Inputs to the topological likelihood (choice 2) for $e+\text{jets}\ t\bar{t}$ events.
The fact that we are using Monte Carlo distributions as input to the topological likelihood $L_t$ raises the question of how well data distributions agree with the Monte Carlo. We compare data and Monte Carlo distributions for preselected events for the transformed variables aplanarity, sphericity, $K^2_{T\min}$, $H_T$, and $HIT\chi^2$. We also compare data and Monte Carlo distributions for preselected events for $E_T$, $P_T^{\mu}(\text{highest})$, and $P_T^{hf}(\text{highest})$. For the contributing fractions of $t\bar{t}$, $Wjjjj$, and QCD we use the fractions determined by the second matrix method that are given in Table XI. The $t\bar{t}$ and $Wjjjj$ distributions are given by Monte Carlo samples described at the beginning of this section. The QCD distribution is taken from data by requiring preselection cuts except that lepton is required to be not isolated. In the case of the $e^+\text{jets}$ this means that the electron did not pass the EM likelihood cut.

The data/Monte Carlo comparisons are shown in Figures 21 - 41 that can be found in Section XI. The Kolmogorov-Smirnov probability that determines if two distributions differ significantly is shown at the bottom left of the histograms. There is relatively good agreement between data and Monte Carlo in all distributions.

### III. SIGNAL AND BACKGROUND DETERMINATION

We use the first and second matrix methods in order to determine the number of signal and background events in the selected data. Below we use the terms “loose”, “preselected”, and “selected” events. Preselected events are those events that pass the selection criteria in Table II and Table III. Loose events are those events that pass the preselection criteria except the isolation criterion. Specifically, $N_{\text{loose}}$ in the $\mu$-jets channel is the number of events passing all preselection criteria except for the muon isolation criterion. $N_{\text{loose}}$ in the $e^+\text{jets}$ channel is the number of events passing all preselection criteria except for the EM likelihood criterion. Selected events are those events that pass the preselection cuts and the topological
The likelihood cut (choice 2).

The first matrix method is used to determine the number of \( t\bar{t} + W jj jj \) \((N^{t\bar{t} + W}_{\text{pre}})\) and QCD\((N^{QCD}_{\text{pre}})\) events after preselection but before applying the topological likelihood cut. This method starts by writing

\[
N_{\text{loose}} = N^{W + t\bar{t}} + N^{QCD}
\]

\[
N_{\text{pre}} = \varepsilon_{\text{sig}} N^{W + t\bar{t}} + \varepsilon_{QCD} N^{QCD}
\]

which can be solved as

\[
N^{W + t\bar{t}} = \frac{N_{\text{pre}} - \varepsilon_{QCD} N_{\text{loose}}}{\varepsilon_{\text{sig}} - \varepsilon_{QCD}} \quad \text{and} \quad N^{QCD} = \frac{\varepsilon_{\text{sig}} N_{\text{loose}} - N_{\text{pre}}}{\varepsilon_{\text{sig}} - \varepsilon_{QCD}}
\]

The input to the first matrix method is given in Table VII. The output from the first matrix method is given in Table VIII. The efficiencies and their errors are taken from the production cross section note for the lepton plus jets decay channel \([9]\). \( N_{\text{loose}} \) and \( N_{\text{pre}} \) were defined in the first paragraph of this section. Here \( \varepsilon_{\text{signal}} \) refers to both \( t\bar{t} \) and \( W jj jj \) events.

We use the second matrix method in order to determine the number of signal and background events in our final sample after all selection criteria. This method is written as

\[
N_{\text{pre}} = N^{t\bar{t}}_{\text{pre}} + N^{W}_{\text{pre}} + N^{QCD}_{\text{pre}}
\]

\[
N_{\text{sel}} = \varepsilon^{t\bar{t}}_{\text{sel}} N^{t\bar{t}}_{\text{pre}} + \varepsilon^{W}_{\text{sel}} N^{W}_{\text{pre}} + \varepsilon^{QCD}_{\text{sel}} N^{QCD}_{\text{pre}}.
\]

and solved as

\[
\varepsilon^{t\bar{t}}_{\text{sel}} = \frac{N_{\text{sel}} - \varepsilon^{W}_{\text{sel}} N_{\text{pre}} - (\varepsilon^{QCD}_{\text{sel}} - \varepsilon^{W}_{\text{sel}}) N^{QCD}_{\text{pre}}}{\varepsilon^{t\bar{t}}_{\text{sel}} - \varepsilon^{W}_{\text{sel}}}
\]

\[
\varepsilon^{W}_{\text{sel}} = \frac{\varepsilon^{W}_{\text{sel}} N_{\text{sel}} - \varepsilon^{t\bar{t}}_{\text{sel}} N_{\text{pre}} + (\varepsilon^{t\bar{t}}_{\text{sel}} - \varepsilon^{QCD}_{\text{sel}}) N^{QCD}_{\text{pre}}}{\varepsilon^{W}_{\text{sel}} - \varepsilon^{t\bar{t}}_{\text{sel}}}
\]

The quantities for the second matrix method and their error for the \( \mu + \text{jets} \) and \( e + \text{jets} \) channels are given in Table IX.

The preselected and selected samples refer to the number of events without and with the topological likelihood \( L_t \) cut. The efficiency of the \( L_t \) cut for \( t\bar{t} \) and \( W jj jj \) events is defined as

\[
\varepsilon = \frac{N_{\text{preselected} + L_t \text{cut}}}{N_{\text{preselected}}}
\]
For $t \bar{t}$ events we calculate $\varepsilon_{sel}^{\ell\ell}$ using the $f^+ = 0.15$ Monte Carlo sample. This minimizes the error due to the variation of the $L_\ell$ efficiency as a function of $f^+$. The variation in the efficiency as a function of $f^+$ (Figure 4) is included in the error for $\varepsilon_{sel}^{\ell\ell}$ listed in Table IX.

The efficiency of the $L_\ell$ cut for QCD events is determined from data. Here the denominator is the number of preselected events for which there are exactly no isolated leptons. In the case of the $\mu$+jets channel, the isolation definition uses cuts on Rat11 and RatTrk. In the case of the $e$+jets channel, the isolation definition uses a cut on the EM likelihood. The numerator is the number of events in the denominator that additionally pass the $L_\ell$ cut.

The resulting number of $t \bar{t}$, $Wjjjj$ and QCD events resulting from the second matrix are given in Table X. We use these numbers of signal and background events to perform ensemble tests and as input into our likelihood used to determine $f^+$. The uncertainties in these numbers include the uncertainty in the topological likelihood selection efficiency, which varies as a function of $f^+$.

One can also determine the number of of $t \bar{t}$, $Wjjjj$ and QCD events in the preselected sample by dividing the number of selected events by the topological likelihood efficiency. The results are given in Table XI and were used in building histograms that compared kinematic variables for preselected data and Monte Carlo events.

IV. TEMPLATES

The input to the maximum likelihood fit requires templates of signal and backgrounds. The $t \bar{t}$ and $Wjjjj$ templates are generated using the Monte Carlo samples described in Section II. The $t \bar{t}$ templates are produced for $f^+$ values from 0.0 to 0.3. The events are required to pass all selection cuts.
The QCD templates are found using data. For QCD, the events are required to pass all selection cuts with one difference. In the $\mu$+jets channel we define a QCD sample by requiring the high $P_T$ muon not to be isolated (i.e. to fail the Rat11 or Rattrk cuts). In the $e$+jets channel we define a QCD sample by requiring the high $P_T$ electron not to pass the EM likelihood cut.

To ease reading, the templates for signal and backgrounds for the $\mu$+jets and $e$+jets decay channels are shown in Section XII. In order to study certain systematic errors we also make templates varying the top quark mass and the jet energy scale corrections. Examples of these variations are also given in Section XII.

When used in the maximum likelihood fit, the templates are rebinned to have five bins. We chose five bins based on a study that varied the number of bins as 2, 5, 10, and 50 bins. The results of this study can be found in Section VI.

Our templates were produced using HITFIT to determine the $b$–jet associated with the leptonic $W$. The object momenta returned from HITFIT’s constrained kinematic fit are used in the calculation of $\cos\theta^*$. In the case where there was no solution in HITFIT we employed a simpler $\chi^2$ method that compares the calculated and known hadronic and leptonic decay top quark masses and hadronic $W$ mass to select the $b$–jet, and used the object momenta from RECO in calculating $\cos\theta^*$. However these cases are a rare circumstance, occurring in about 0.5% of events.

HITFIT selects the correct $b$–jet 57%, 58%, and 57% of the time using ALPGEN $t\bar{t}$ samples with $f^+ = 0.0$, 0.15, and 0.30. The simpler $\chi^2$ method selects the correct $b$–jet 55% of the time for the ALPGEN $t\bar{t}$ sample with $f^+ = 0.0$. In approximately 72% of Monte Carlo events both methods selected the same $b$–jet.

The nominal JES corrections were applied to both data and Monte Carlo. The nominal parton and eta dependent correction were used in selecting the $b$–jet associated with the leptonic $W$ (either with HITFIT or the simpler $\chi^2$ method).

V. MAXIMUM LIKELIHOOD FIT

We perform a binned maximum likelihood fit to extract the value of $f^+$, the fraction of V+A in the top decay, most consistent with the data. As input to the fit we have the distributions of $\cos\theta^*$ in: the selected data events, ALPGEN $t\bar{t}$ Monte Carlo with $f^+ = 0.00$, 0.05, 0.10, 0.15, 0.20, 0.25, and 0.30, ALPGEN $Wjjjj$ Monte Carlo, and QCD background from data. We also note in the ALPGEN V+A samples, the fraction $f^0$ is constant (70%) for all samples.

For each $f^+$ value for which a template exists, we compute the likelihood of the data to be consistent with the sum of signal and background templates. The likelihood is computed by multiplying the Poisson probabilities of each template bin being consistent with the data, using a method in which the finite template statistics are explicitly accounted for [11]. We also have a prior expectation for the normalization of the background, which is expressed with a Gaussian term in the likelihood. We define the likelihood as

$$L(f^+) = \prod_{i=1}^{N_{bkg}} e^{(n_i - \bar{n}_{i,d})^2/2\sigma_{i,d}^2} \times \prod_{j=1}^{N_{binc}} P(d_j; n_j) \times \prod_{k=0}^{N_{n_{source}}} B(a_{jk}; A_{jk}, p_k). \quad (8)$$

where $P(x; y)$ is the Poisson probability for $x$ events given an average value $y$ and $B(m; n, p)$ is the
binomial probability for observing \( m \) events out of \( n \) possible given probability \( p \).

In the Gaussian term, \( N_{\text{bkg}} \) is the number of background sources (\( Wjjjjj \) and QCD in this analysis), \( n_b, i \) is the observed number of events for the \( i \)th background (i.e. from the second matrix method), \( \sigma_{b,i} \) is the systematic uncertainty on the observed number, and \( n_b, i \) is the expected number of events for the \( i \)th background. In the Poisson term, \( d_j \) is the number of data events in the \( j \)th bin of the \( \cos\theta^* \) distribution and \( n_j \) is the predicted number of signal and background events in the \( j \)th bin of the distribution. In the binomial term, \( a_{jk} \) is the actual number of Monte Carlo signal and background events in the \( j \)th template bin, \( A_{jk} \) is the (unknown) expected number of Monte Carlo signal and background events in the \( j \)th template bin and \( p_k \) is the probability (strength factor) for observing the \( k \)th source (\( t\bar{t}, Wjjjjj \) and QCD). To be precise, \( p_k = n_k/N_k \) where \( n_k \) is the number of events from a given source in the data sample, and \( N_k \) is the number of entries in the template used to model that source.

We minimize the \( -\ln L \) for each trio of templates (two background templates and one \( f^+ \) template) (the \( a_{jk} \) and data distribution (the \( d_j \)). The minimization is with respect to the \( n_k \) and the expected number of Monte Carlo (template) signal and background events \( A_{jk} \). The procedure is simplified by performing the minimization of the \( A_{jk} \) analytically. The result of the fit then gives the predicted number of events from all sources in each bin \( n_{\text{all},j} \)

\[
n_{\text{all},j} = \sum_{k=1}^{N_{\text{source}}} p_k A_{jk} \tag{9}
\]

The procedure is repeated for all \( f^+ \) templates.

For emphasis we repeat that the minimization of the \( -\ln L \) is performed using the likelihood defined as above. However the interpretation of \( L \) requires some care. The first term is necessary since there is not enough difference in the \( \cos\theta^* \) shapes between signal and background to determine the background level in the absence of an input prediction. The second term, the Poisson probability of consistency between the data and the best possible \( f^+ \) model, is similar to the term that would appear in a ”standard” binned Poisson likelihood fit. The distinction is that a standard fit would compare the data directly to the available templates, while in this case we compare the data to the best possible template distribution, consistent with the template statistics.

The third term is the binomial probability of the best possible template distribution fluctuated to give the particular set of templates input to the fit. It accounts for the finite statistics of the Monte Carlo templates used. This binomial term is clearly necessary when maximixing \( L \) at each \( f^+ \) value. Without it, the templates would be free to fluctuate to look exactly like the data.

However, when comparing the results of separate fits at different values of \( f^+ \), this term is not relevant. It can be thought of as an ”internal penalty” paid in the fit at each \( f^+ \) value as the templates try to adjust themselves to match the data. Indeed, including this term in \( L \) when comparing \( L \) at different values of \( f^+ \) leads to a correlation between the template statistics and the value of \( L \). This correlation led to a noticable bias in earlier versions of our analysis because the number of Monte Carlo events passing the event selection increases with \( f^+ \). Therefore, when comparing the relative likelihood of the various \( f^+ \) terms, we consider only the contribution of the Gaussian and Poisson terms.

To summarize, we minimize \( -\ln L \) using the likelihood given above. However when comparing values of the likelihood at each value of \( f^+ \) we take the value of \( -\ln L \) to be that using only the Gaussian and Poisson terms. This prescription still accounts for finite template statistics but removes the correlation between \( L \) and the template statistics. The result is a distribution of \( -\ln L \) points versus \( f^+ \). We fit these points to a
parabola to estimate the likelihood as a function of $f^+$. In the event that multiple channels enter the fit ($e^+$-jets and $\mu^+$-jets in this case) the $-\ln L$ points are calculated as described above for each channel separately, then summed. A parabola is fit to the summed points to determine the overall likelihood as a function of $f^+$.

A. Bayesian interpretation of results

Since in our assumed model $f^+$ must lie between 0 and 0.30, we use a Bayesian technique to determine a 68% CL range for the true value of $f^+$. We choose to use a flat prior probability in $f^+$. With this choice, finding a Bayesian confidence interval is equivalent to integrating the likelihood curve. If the parabola fit to the $-\ln L$ points has its minimum in the allowed range, we take the value of that minimum (i.e. the maximum of $L$) as the most likely value $x_{ML}$. We then find the points $x_{\min}$ and $x_{\max}$ such that:

$$\frac{\int_{x_{\min}}^{x_{ML}} L(x) \, dx}{\int_{0}^{0.30} L(x) \, dx} = \frac{\int_{x_{ML}}^{x_{\max}} L(x) \, dx}{\int_{0}^{0.30} L(x) \, dx} = 0.34$$

If $x_{ML}$ lies outside the allowed range (or close enough to the boundary that the $x_{\max}$ or $x_{\min}$ cannot be found by both equations above), a single-sided range is reported:

$$\frac{\int_{0}^{x_{\max}} L(x) \, dx}{\int_{0}^{0.30} L(x) \, dx} = 0.68$$

or:

$$\frac{\int_{x_{\min}}^{0.30} L(x) \, dx}{\int_{0}^{0.30} L(x) \, dx} = 0.68$$

If $x_{ML}$ is less than (or close to) 0.0, then $x_{\min} = 0$ and $x_{\max}$ is calculated. If $x_{ML}$ is greater than (or close to) 0.30, then $x_{\max} = 0.30$ and $x_{\min}$ is calculated. This in all cases there is both an $x_{\min}$ and $x_{\max}$.

In the case where the $-\ln L$ points form an “upside-down” parabola, $x_{ML}$ is taken to be at the physical boundary ($f^+ = 0.0$ or 0.30) with the smallest value of $-\ln L$.

VI. RESULTS FROM ENSEMBLE TESTS

We test the performance of the maximum likelihood fit by means of Monte Carlo ensemble tests. For these tests, we assume a true value of $f^+$ and form a mock data set by drawing events from the appropriate Monte Carlo samples. Each data set so formed has the same number of $\mu^+$-jets and $e^+$-jets as we observe in
the real data sample (Table X), but the number of signal and background is varied according to the binomial distribution. (Also once the number of background events in a particular mock data set is determined, the number of $Wjjjj$ and QCD events is allowed to fluctuate binomially as well).

The mock data set is then fit according to the same procedure used for fitting the real data. By repeating the process a large number of times (1000 unless otherwise stated) we can investigate the statistical properties of the maximum likelihood fit. The results are given in Table XIII. Note that while the general trend is reasonable (the average of the most likely value of $f^+$ increases as the true $f^+$ increases), the change in the average result is much less than the change in true $f^+$. This is an unavoidable consequence of having the result defined over a finite range of values.

Also shown in the table is the average size of the 68% confidence interval (CL) and the fraction of times in which the 68% CL range contains the true value of $f^+$. Note the average size of the 68% CL is slightly over half the allowed range of $f^+$. The fact that the fraction of times in which the 68% CL contains the true $f^+$ value is 82% for $f^+=0.15$ is a reflection of this average size. Both the fraction of times in which the 68% CL contains the true value of $f^+$ and the fraction of times there is a good parabola are symmetric about $f^+=0.15$ which makes sense. The main point here is that these ensemble tests show that the Bayesian confidence interval behaves properly. When one averages over all possible values of $f^+$, the probability for the true $f^+$ to be in the 68% Bayesian confidence interval is 69.1%, which is reasonable agreement.

Histograms of the Bayesian estimators for $f^+$ for ensemble tests at each true $f^+$ value are shown in Figures 5-11.

In the tests ensemble tests above, the $\cos\theta^*$ templates each contained five bins. We have studied whether increasing or decreasing the bins affects the results. We used templates with 2, 5, 10, and 50 bins. The results are shown in Tables XII- XV.

The best choice would have the average result tracking the true result, a small 68% CL region, approximately 68% of the ensembles in the 68% CL region, and a large fraction of “right-side-up” parabolas. As the results in Tables XII- XV show, there is no one choice of binning that is ideal. One sees that the fraction of fits with a “right-side-up” parabola decreases as the number of bins increase, while the average width of the 68% CL region decreases slightly. We choose to use five bins.

<table>
<thead>
<tr>
<th>True $f^+$</th>
<th>Ave. Bayesian result</th>
<th>Ave. size of 68% CL range</th>
<th>Fraction in 68% CL range</th>
<th>Fraction with good parabolas</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.08</td>
<td>0.17</td>
<td>0.672</td>
<td>0.915</td>
</tr>
<tr>
<td>0.05</td>
<td>0.11</td>
<td>0.18</td>
<td>0.605</td>
<td>0.951</td>
</tr>
<tr>
<td>0.10</td>
<td>0.13</td>
<td>0.17</td>
<td>0.629</td>
<td>0.962</td>
</tr>
<tr>
<td>0.15</td>
<td>0.14</td>
<td>0.17</td>
<td>0.878</td>
<td>0.962</td>
</tr>
<tr>
<td>0.20</td>
<td>0.17</td>
<td>0.18</td>
<td>0.678</td>
<td>0.976</td>
</tr>
<tr>
<td>0.25</td>
<td>0.17</td>
<td>0.17</td>
<td>0.629</td>
<td>0.986</td>
</tr>
<tr>
<td>0.30</td>
<td>0.21</td>
<td>0.17</td>
<td>0.625</td>
<td>0.989</td>
</tr>
</tbody>
</table>

TABLE XII: Results of Monte Carlo ensemble tests on mock data samples that model the current real data sample. The results in this table are for $\cos\theta^*$ templates having two bins.
<table>
<thead>
<tr>
<th>True $f^+$</th>
<th>Ave. Bayesian result</th>
<th>Ave. size of</th>
<th>Fraction in</th>
<th>Fraction with</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>68% CL range</td>
<td>68% CL range</td>
<td>good parabolas</td>
</tr>
<tr>
<td>0.00</td>
<td>0.07</td>
<td>0.16</td>
<td>0.697</td>
<td>0.704</td>
</tr>
<tr>
<td>0.05</td>
<td>0.12</td>
<td>0.17</td>
<td>0.590</td>
<td>0.822</td>
</tr>
<tr>
<td>0.10</td>
<td>0.12</td>
<td>0.17</td>
<td>0.692</td>
<td>0.794</td>
</tr>
<tr>
<td>0.15</td>
<td>0.15</td>
<td>0.17</td>
<td>0.687</td>
<td>0.867</td>
</tr>
<tr>
<td>0.20</td>
<td>0.18</td>
<td>0.17</td>
<td>0.591</td>
<td>0.868</td>
</tr>
<tr>
<td>0.25</td>
<td>0.20</td>
<td>0.17</td>
<td>0.697</td>
<td>0.863</td>
</tr>
<tr>
<td>0.30</td>
<td>0.21</td>
<td>0.16</td>
<td>0.633</td>
<td>0.819</td>
</tr>
</tbody>
</table>

TABLE XIII: Results of Monte Carlo ensemble tests on mock data samples that model the current real data sample. The results in this table are for cos$\theta^*$ templates having five bins.

<table>
<thead>
<tr>
<th>True $f^+$</th>
<th>Ave. Bayesian result</th>
<th>Ave. size of</th>
<th>Fraction in</th>
<th>Fraction with</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>68% CL range</td>
<td>68% CL range</td>
<td>good parabolas</td>
</tr>
<tr>
<td>0.00</td>
<td>0.05</td>
<td>0.16</td>
<td>0.716</td>
<td>0.368</td>
</tr>
<tr>
<td>0.05</td>
<td>0.11</td>
<td>0.17</td>
<td>0.585</td>
<td>0.776</td>
</tr>
<tr>
<td>0.10</td>
<td>0.12</td>
<td>0.17</td>
<td>0.694</td>
<td>0.778</td>
</tr>
<tr>
<td>0.15</td>
<td>0.15</td>
<td>0.17</td>
<td>0.793</td>
<td>0.810</td>
</tr>
<tr>
<td>0.20</td>
<td>0.17</td>
<td>0.17</td>
<td>0.692</td>
<td>0.839</td>
</tr>
<tr>
<td>0.25</td>
<td>0.20</td>
<td>0.16</td>
<td>0.704</td>
<td>0.800</td>
</tr>
<tr>
<td>0.30</td>
<td>0.21</td>
<td>0.17</td>
<td>0.637</td>
<td>0.768</td>
</tr>
</tbody>
</table>

TABLE XIV: Results of Monte Carlo ensemble tests on mock data samples that model the current real data sample. The results in this table are for cos$\theta^*$ templates having ten bins.

<table>
<thead>
<tr>
<th>True $f^+$</th>
<th>Ave. Bayesian result</th>
<th>Ave. size of</th>
<th>Fraction in</th>
<th>Fraction with</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>68% CL range</td>
<td>68% CL range</td>
<td>good parabolas</td>
</tr>
<tr>
<td>0.00</td>
<td>0.05</td>
<td>0.16</td>
<td>0.775</td>
<td>0.368</td>
</tr>
<tr>
<td>0.05</td>
<td>0.11</td>
<td>0.17</td>
<td>0.624</td>
<td>0.511</td>
</tr>
<tr>
<td>0.10</td>
<td>0.11</td>
<td>0.17</td>
<td>0.753</td>
<td>0.677</td>
</tr>
<tr>
<td>0.15</td>
<td>0.15</td>
<td>0.17</td>
<td>0.830</td>
<td>0.661</td>
</tr>
<tr>
<td>0.20</td>
<td>0.18</td>
<td>0.17</td>
<td>0.726</td>
<td>0.635</td>
</tr>
<tr>
<td>0.25</td>
<td>0.19</td>
<td>0.17</td>
<td>0.622</td>
<td>0.574</td>
</tr>
<tr>
<td>0.30</td>
<td>0.22</td>
<td>0.16</td>
<td>0.691</td>
<td>0.387</td>
</tr>
</tbody>
</table>

TABLE XV: Results of Monte Carlo ensemble tests on mock data samples that model the current real data sample. The results in this table are for cos$\theta^*$ templates having 50 bins.
FIG. 5: Bayesian results for $f^+$ for ensemble tests with true $f^+ = 0.0$.

FIG. 6: Bayesian results for $f^+$ for ensemble tests with true $f^+ = 0.05$.

FIG. 7: Bayesian results for $f^+$ for ensemble tests with true $f^+ = 0.10$. 
FIG. 8: Bayesian results for $f^+$ for ensemble tests with true $f^+=0.15$.

FIG. 9: Bayesian results for $f^+$ for ensemble tests with true $f^+=0.20$.

FIG. 10: Bayesian results for $f^+$ for ensemble tests with true $f^+=0.25$. 
TABLE XVI: Summary of the systematic errors on $f^+$. 

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top mass</td>
<td>0.11</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.04</td>
</tr>
<tr>
<td>W + jets model</td>
<td>0.08</td>
</tr>
<tr>
<td>$t\bar{t}$ model</td>
<td>0.05</td>
</tr>
<tr>
<td>Total</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Statistical uncertainties in both the data and templates are handled by the likelihood fit using Poisson statistics for the data and binomial statistics for the templates.

Sources of systematic errors arise from the uncertainties in the top mass, jet energy scale, and Monte Carlo models of signal and background. Variations in these parameters can change the measurement in two ways: by altering the estimate of the background in the final sample (i.e., if the final selection efficiency changes) and by modifying the shape of the $\cos \theta^*$ templates.

We estimate the magnitude of these uncertainties by running ensemble tests using the standard templates, but with the mock data drawn from samples with the appropriate parameter varied. The signal and background content of the ensembles is fixed to the values we expect using our nominal final selection efficiencies, but the background constraint input to the maximum likelihood fit is varied to reflect the shifted final selection efficiency. (The nominal and varied selection efficiencies are reported in Table VI). To minimize statistical fluctuations due to the ensemble size we increase the number of events in the ensemble to be 100 times that observed in our data sample. The results are summarized in Table XVI, and details of the calculations are given below.

To estimate the systematic error due to the uncertainty of the top quark mass we use $f^+ =0.0$ samples with the top quark mass set to 170, 175, and 180 GeV. The average fit values are given in Table XVII. We take the average of the upwards and downwards variations as our systematic ($\pm 0.11$).

The jet energies against which the selection criteria are applied contain the nominal jet energy scale corrections. Additionally, we apply parton and eta dependent corrections to these jet energies when calculating $\cos \theta^*$. 

Fig. 11: Bayesian results for $f^+$ for ensemble tests with true $f^+=0.30$. 

VII. STATISTICAL AND SYSTEMATIC ERRORS
To estimate the systematic error due to the uncertainty of the jet energy scale we vary the jet energy scale by $\pm 1\sigma$ about the nominal value. The nominal value is used to... We first modify the jet energies to have the values given by varying the jet energy scale by $\pm 1\sigma$. The missing $E_T$ is then adjusted to account for changes in the relevant components of the jet scale shift (e.g. missing $E_T$ is changed to reflect uncertainty in hadronic response, but not uncertainty in out-of-cone showering). We use these new jet energies and missing $E_T$ when applying the selection criteria. Next we apply parton and eta dependent corrections to the uncorrected jet energies, but now vary these parton and eta dependent corrections by $\pm 1\sigma$. The parton and eta dependent corrections are used to ... We then calculate $\cos\theta^*$ using these jet energies within HitFit.

The average fit values found when varying the jet energy scale are given in Table XVIII. For the systematic error we sum the range of values for $f^+ = 0.0$, 0.15, and 0.30 and divide by 6. This gives a systematic error for the jet energy scale of $0.04$.

Another source of systematic uncertainty is the model of the $Wjjjj$ background. The nominal background sample used is the Higgs’ group Tune A ALPGEN sample. An alternate sample is the Top group’s iqopt10 ALPGEN sample, which was generated with a factorization scale of $< p_T(jet) > ^2$. The variation in results using the two samples is reported in Table XIX. We take the average of the variations seen at the different $f^+$ values, 0.08, as our systematic.

Finally we consider the model of $t\bar{t}$ decays. As an alternative to the nominal Alpgen $t\bar{t}$ sample, we generate Pythia samples of $t\bar{t}$ in the $\mu^+$jets decay channel, passed through a parton-level selection such that the surviving events have a $\cos\theta^*$ distribution identical to that expected for purely right-handed, longitudinal, or left-handed $W$’s. We then combine these three separate sets of events in the correct proportions to mimic any given $f^+$ value. The variations seen in ensemble tests when events are drawn from these samples but fit using the nominal ALPGEN $t\bar{t}$ templates are shown in Table XX. We take one half of the average variation, 0.04, to be the systematic uncertainty.

<table>
<thead>
<tr>
<th>$f^+$ Fraction</th>
<th>$m_t$</th>
<th>$m_t$</th>
<th>$m_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>170</td>
<td>175</td>
<td>180</td>
</tr>
<tr>
<td>0.0</td>
<td>-0.18</td>
<td>-0.02</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table XVII: Average maximum likelihood fit values for $m_t = 170$, 175, and 180 GeV.

<table>
<thead>
<tr>
<th>$f^+$ Fraction</th>
<th>JES</th>
<th>JES</th>
<th>JES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$+\sigma$</td>
<td>nominal</td>
<td>$-\sigma$</td>
</tr>
<tr>
<td>0.0</td>
<td>-0.03</td>
<td>-0.07</td>
<td>0.00</td>
</tr>
<tr>
<td>0.15</td>
<td>0.11</td>
<td>0.14</td>
<td>0.18</td>
</tr>
<tr>
<td>0.30</td>
<td>0.31</td>
<td>0.30</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Table XVIII: Average maximum likelihood fit values for jet energy scale values of $+\sigma$, nominal, and $-\sigma$.

<table>
<thead>
<tr>
<th>$f^+$ Fraction</th>
<th>Higgs Tune A W jjjj iqopt10 W jjjj</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monte Carlo</td>
</tr>
<tr>
<td>0.0</td>
<td>-0.07</td>
</tr>
<tr>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>0.30</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table XIX: Average maximum likelihood fit values for nominal and alternate $Wjjjj$ Monte Carlo samples.
\begin{tabular}{ccc}
\hline
\(f^+\) Fraction & ALPGEN \(t\bar{t}\) & PYTHIA \(t\bar{t}\) \\
\hline
0.0 & -0.28 & -0.20 \\
0.15 & -0.16 & 0.11 \\
0.30 & 0.25 & 0.22 \\
\hline
\end{tabular}

TABLE XX: Average maximum likelihood fit values for nominal and alternate \(t\bar{t}\) Monte Carlo samples.

<table>
<thead>
<tr>
<th>Result for (f^+)</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0 &lt; f^+ &lt; 0.131)</td>
<td>68%</td>
</tr>
<tr>
<td>(0 &lt; f^+ &lt; 0.236)</td>
<td>90%</td>
</tr>
<tr>
<td>(0 &lt; f^+ &lt; 0.253)</td>
<td>95%</td>
</tr>
</tbody>
</table>

TABLE XXI: Bayesian result for \(f^+\) for various confidence levels. This result includes statistical errors only.

VIII. RESULTS FROM DATA

The results of applying our maximum likelihood fit to the \(\cos\theta^*\) distribution observed in the data are shown in Figure 12 for \(\mu^+\) jets events, Figure 13 for \(e^+\) jets events, and Figure 14 for the combined data sample. The parabola that best fits the combined \(-\ln L\) points has a minimum outside the physically-allowed region (at \(f^+ = -0.105 \pm 0.188\)). The Bayesian confidence intervals for different confidence levels are given in Table XXI. This result includes statistical errors only.

![Figure 12](image-url)

FIG. 12: Result of the maximum likelihood fit for \(f^+\) on the \(\mu^+\) jets data.

We also show plots comparing the data distribution to the best fit model (\(f^+ = 0.0\)). In Figures 15-17 the data is shown as the points with error bars, the best fit signal template as the dashed histogram, the best fit background template as the dotted histogram, and the sum as the solid histogram. The best fit templates are normalized according to the fitted signal and background levels at the best fit \(f^+\) point (0.0 in our case).

We also give the number of signal and background events resulting from the best fit using each \(f^+\) signal
The systematic errors in the last section are included in the fit by convoluting a Gaussian function with a width given by the total systematic error with the Gaussian resulting from the maximum likelihood fit. The
FIG. 15: Comparison of $\mu$+jets data (points with errors bars) to the sum of the best-fit templates of signal and background (solid histogram). The signal and background contributions are shown separately as the dashed and dotted histogram.

TABLE XXII: Number of signal and background events resulting from the best fit using each $f^+$ signal model

<table>
<thead>
<tr>
<th>Signal Model</th>
<th>$\mu$+jets</th>
<th>$t\bar{t}$</th>
<th>$Wjjjj$+QCD</th>
<th>$e$+jets</th>
<th>$t\bar{t}$</th>
<th>$Wjjjj$+QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f^+$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>10.0</td>
<td>19.8</td>
<td>23.3</td>
<td>23.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>10.0</td>
<td>19.8</td>
<td>24.6</td>
<td>23.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>9.3</td>
<td>19.9</td>
<td>24.3</td>
<td>23.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>9.3</td>
<td>19.9</td>
<td>23.7</td>
<td>23.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>9.1</td>
<td>19.9</td>
<td>23.7</td>
<td>23.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>8.3</td>
<td>19.9</td>
<td>22.8</td>
<td>23.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>8.0</td>
<td>19.9</td>
<td>21.3</td>
<td>23.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE XXIII: Bayesian result for $f^+$ for various confidence levels. This result includes both statistical and systematic errors.

<table>
<thead>
<tr>
<th>Result for $f^+$</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 &lt; f^+ &lt; 0.159$</td>
<td>68%</td>
</tr>
<tr>
<td>$0 &lt; f^+ &lt; 0.244$</td>
<td>90%</td>
</tr>
<tr>
<td>$0 &lt; f^+ &lt; 0.267$</td>
<td>95%</td>
</tr>
</tbody>
</table>

results including systematic errors for different confidence levels are given in Table XXIII. The maximum likelihood distribution including statistical errors and including both statistical and systematic errors is shown in Figure 18. These results are interpreted as, for any one experiment, there is a $x\%$ chance that the true value of $f^+$ lies within the $x\%$ confidence interval.

The standard model value of $f^+ = 0$ is consistent with our results, but increased data and Monte Carlo statistics will be required to rule out any non-SM value.
FIG. 16: Comparison of e+jets data (points with error bars) to the sum of the best-fit templates of signal and background (solid histogram). The signal and background contributions are shown separately as the dashed and dotted histogram.

IX. FREQUENTIST INTERPRETATION

In order to compare this analysis with that using b-tagged events we also construct confidence intervals for our result using a frequentist approach based on a paper by Feldman and Cousins [12].

Closely following the pedagogy of Feldman and Cousins, consider first the Poisson case of a measured number of events \( n \) given \( \mu \) signal events and \( b \) expected (known) background events. One wishes to determine confidence intervals for \( \mu \) given \( n \).

The Feldman and Cousins approach makes use of an ordering principle that is based on likelihood ratios to determine the acceptance regions (allowed regions of \( n \) given \( \mu \)).

For each \( n \), \( \mu_{\text{best}} \) is defined as the value of \( \mu \) that maximizes the probability of finding \( n \). The likelihood ratio is a measure of how good the “proposed” mean signal value, \( \mu_o \), is to \( \mu_{\text{best}} \).

\[
R = \frac{P(n|\mu)}{P(n|\mu_{\text{best}})}. 
\]

(10)

One calculates \( R \) for each value of \( n \) and values of \( n \) are added to the acceptance region in decreasing order of \( R \). This ordering continues until the sum of the probabilities \( P(n|\mu) \) meets the desired confidence level (68%, 90%, etc.) The acceptance region for each value of \( \mu \) is computed in this manner. For a measured value of \( n \), the confidence interval is the set of all \( \mu \) for which the acceptance region contains the actual measured value of \( n \).

In this analysis, we do not have a single measured number of events \( n \) but rather several measured numbers that make up bins in a histogram. Again, closely following the pedagogy of Feldman and Cousins...
[12], consider that we have a set of measured data \( N \equiv \{ n_i \} \), together with an assumed expected (known) background \( B \equiv \{ b_i \} \) and a signal contribution \( T \equiv \{ \mu_i \} \). In this case each bin \( i \) corresponds to a Poisson process [13].

\[
P(n_i|\mu_i) = (\mu + b)^n \cdot \frac{\exp[-(\mu + b)]}{n!}.
\]  

Ordering in this case is carried out using \( \Delta \chi^2 = 2(\ln P - \ln P_{\text{best}}) \) where \( P \) is the probability of observing \( N \) given \( T \) (or \( T_{\text{best}} \)). Feldman and Cousins and reference [13] use

\[
\Delta \chi^2 = 2 \sum_i \left[ \mu_i - \mu_{\text{best}} + n_i \ln \left( \frac{\mu_{\text{best}} + b_i}{\mu_i + b_i} \right) \right]
\]  

and we’ll call this definition 1. Alternatively, since \( \Delta \chi^2 = 2(\ln P - \ln P_{\text{best}}) \), one can use \( \ln P = \ln L \) where

\[
L(f^+) = \prod_{i=1}^{N_{\text{bkg}}} e^{(n_i - n_{bkg})^2/(2n_{bkg})} \times \prod_{j=1}^{N_{\text{bkg}}} P(d_j; n_j) \times \prod_{k=0}^{N_{\text{sig}}(\text{res})} B(a_{jk}; A_{jk}, p_k).
\]  

as used earlier in this analysis. We’ll call this definition 2.

Using definition 2, we proceed as follows.

- Perform ensemble tests for each \( f^+ \) Monte Carlo sample using the standard \( \cos \theta* \) templates. For each mock data sample, calculate \( \Delta \ln L = \ln L - \ln L_{\text{best}} \). The value of \( \ln L_{\text{best}} \) is that evaluated at the minimum of the \( \ln L \) fit. In the case where minimum is outside the physical boundar (0.0 or 0.3)
FIG. 18: Results of the combined $e$+jets and $\mu$+jets maximum likelihood fits including statistical errors only (solid line) and including both statistical and systematic errors (dashed line).

\[
\begin{array}{l}
\ln L_{\text{best}} \text{ is evaluated at the boundary. The value of } \ln L \text{ is that evaluated at the true } f^+ \text{ value of the mock data sample.} \\

\text{The values of } \Delta \ln L = \ln L - \ln L_{\text{best}} \text{ are histogrammed for each set of ensemble tests performed at the different values of } f^+. \text{ The histograms at each } f^+ \text{ are integrated to find that value of } \Delta \ln L = \Delta \ln L_{\text{critical}} \text{ corresponding to the desired confidence interval (68%, 90%, etc.) This is the acceptance region for each value of } f^+. \\

\text{A plot is made of } \Delta \ln L_{\text{critical}} \text{ for each } f^+ \text{ ensemble test.} \\

\text{The } - \ln L \text{ curve from the data (or some mock data sample) is plotted on the same graph. The points or point where the two curves intersect give the desired confidence interval.}
\end{array}
\]

Using definition 2 for $\Delta \chi^2$ and following the steps itemized above, the frequentist approach gives the limits for various confidence levels in Table XXIV. This result includes statistical errors only.

Systematic errors can be included in a similar manner to that used in the Bayesian approach. That is, one convolutes a Gaussian function with a width given by the total systematic error with the Gaussian resulting from the maximum likelihood fit. The resulting $- \ln L$ curve is plotted on the same graph as the $\Delta \ln L_{\text{critical}}$ points as was done above. The results are given in Table XXV. The acceptance curves and the $- \ln L$ curves for statistical errors only and combined systematic and statistical errors are shown in Figure...
TABLE XXV: Frequentist result for $f^+$ for various confidence levels. This result includes both statistical and systematic errors.

<table>
<thead>
<tr>
<th>Confidence Interval</th>
<th>0.0</th>
<th>0.05</th>
<th>0.10</th>
<th>0.15</th>
<th>0.20</th>
<th>0.25</th>
<th>0.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>68%</td>
<td>0.679</td>
<td>0.681</td>
<td>0.676</td>
<td>0.677</td>
<td>0.687</td>
<td>0.668</td>
<td>0.694</td>
</tr>
<tr>
<td>90%</td>
<td>0.900</td>
<td>0.892</td>
<td>0.916</td>
<td>0.890</td>
<td>0.887</td>
<td>0.903</td>
<td>0.898</td>
</tr>
<tr>
<td>95%</td>
<td>0.952</td>
<td>0.942</td>
<td>0.961</td>
<td>0.939</td>
<td>0.945</td>
<td>0.954</td>
<td>0.949</td>
</tr>
</tbody>
</table>

TABLE XXVI: Given a true $f^+$, the fraction of times that the true value of $f^+$ falls within the Feldman-Cousins confidence interval.

19. This means that 95% frequentist confidence interval runs from 0 to 0.257. The frequentist confidence interval is constructed in such a way that in 95% of mock Monte Carlo experiments, the true value of $f^+$ lies within the given 95% confidence interval.

![FIG. 19: Acceptance curves for 68%, 90%, and 95% confidence intervals. Also shown are the results of the combined $e$+jets and $\mu$+jets maximum likelihood fits including statistical errors only (solid line) and including both statistical and systematic errors (dashed line).](image)

Just as in the case of the Bayesian interpretation, we can use ensemble tests to check whether the frequentist approach behaves sensibly. Table XXVI gives the fraction of times that the true value of $f^+$ falls within the Feldman-Cousins confidence interval. Thus the Feldman-Cousins coverage behaves sensibly.

Alternatively, one can use definition 1 for $\Delta \chi^2$ instead of definition 2 which uses $\Delta \ln L$. Following the procedure of [13] we find the confidence intervals for statistical errors only in Table XXVII.

Systematic uncertainties in this case are included by re-computing the acceptance intervals with systematic effects included, again following the procedure in [13]. This is done by re-running the MC ensemble tests used to find $\Delta \chi^2_{critical}$. The samples from which the mock events are drawn are fluctuated by replacing...
the mean $\mu$ in the Poisson distribution for each bin with a random number chosen from a Gaussian with mean $\mu$ and a width corresponding to the systematic uncertainty. This allows for a direct comparison with reference [13]. The acceptance curves and the $-\ln L$ curve are shown in Figure 20.

![Feldman and Cousins Confidence Intervals](image)

**FIG. 20:** Acceptance curves for 68%, 90%, and 95% confidence intervals. The acceptance curves are for statistical errors only as well as both statistical and systematic errors (labeled as “all”). Also shown is the result of the combined $e$+jets and $\mu$+jets maximum likelihood fit.

### X. CONCLUSIONS

We have measured the fraction of right-handed $W$’s ($f^+$) in top decays using the lepton plus jets decay channels. Using a Bayesian interpretation for confidence intervals and including both statistical and systematic uncertainties we find

$$0 < f^+ < 0.159 \text{ (68\% CL)}$$
This means, for any one experiment, there is a 95% chance that the true value of $f^+$ lies within the 95% confidence interval.

Using a frequentist interpretation for confidence intervals and including both statistical and systematic uncertainties we find

$$0 < f^+ < 0.137 \ (68\% \ CL)$$

$$0 < f^+ < 0.201 \ (90\% \ CL)$$

$$0 < f^+ < 0.257 \ (95\% \ CL)$$

This means that 95% frequentist confidence interval runs from 0 to 0.257. The frequentist confidence interval is constructed in such a way that in 95% of mock Monte Carlo experiments, the true value of $f^+$ lies within the given 95% confidence interval.

This measurement is in agreement with the Standard Model prediction of $f^+ = 0.0$.

**XI. DATA/MONTE CARLO COMPARISON PLOTS**

This section contains plots comparing how well data distributions agree with the Monte Carlo. We compare data and Monte Carlo distributions for preselected events for the transformed variables aplanarity, sphericity, $K_{T_{\text{min}}}$, $H_T$, and HITFIT $\chi^2$. We also compare data and Monte Carlo distributions for preselected events for $E_T$, $P_T^{(\text{highest})}$, and $P_T^{\text{jet}(\text{highest})}$. For the contributing fractions of $t\bar{t}$, $Wjjjj$, and QCD we use the fractions determined by the second matrix method that are given in Table XI. The $t\bar{t}$ and $Wjjjj$ distributions are given by Monte Carlo samples described at the beginning of this section. The QCD distribution is taken from data by requiring preselection cuts except that lepton is required to be not isolated. In the case of the $e+$jets this means that the electron did not pass the EM likelihood cut.

The data/Monte Carlo comparisons are shown in Figures 21- 41. For each variable comparison the figure on the left shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions while the figure on the right shows the sum of the contributions. The Kolmogorov-Smirnov probability that determines if two distributions differ significantly is shown at the bottom left of the histograms. There is relatively good agreement between data and Monte Carlo in all distributions.
FIG. 21: Data/Monte Carlo comparison for aplanarity for preselected $\mu+$jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

FIG. 22: Data/Monte Carlo comparison for sphericity for preselected $\mu+$jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.
FIG. 23: Data/Monte Carlo comparison for $H_{T\gamma}$ for preselected $\mu$+jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

FIG. 24: Data/Monte Carlo comparison for $K_{T\min}$ for preselected $\mu$+jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.
FIG. 25: Data/Monte Carlo comparison for $H_T$ for preselected $\mu$+jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

FIG. 26: Data/Monte Carlo comparison for HITFIT $\chi^2$ for preselected $\mu$+jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.
FIG. 27: Data/Monte Carlo comparison for $L_1$ for preselected $\mu$+jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

FIG. 28: Data/Monte Carlo comparison for $E_T$ for preselected $\mu$+jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.
FIG. 29: Data/Monte Carlo comparison for $P_{T}^{\mu}$ (highest) for preselected $\mu$+jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

FIG. 30: Data/Monte Carlo comparison for $P_{T}^{\mu}$ (highest) for preselected $\mu$+jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.
FIG. 31: Data/Monte Carlo comparison for aplanarity for preselected $e+\text{jets}$ events. The left figure shows the individual $t\bar{t}$, $W_{jjjj}$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

FIG. 32: Data/Monte Carlo comparison for sphericity for preselected $e+\text{jets}$ events. The left figure shows the individual $t\bar{t}$, $W_{jjjj}$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.
FIG. 33: Data/Monte Carlo comparison for $H_{T2}$ for preselected e+jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

FIG. 34: Data/Monte Carlo comparison for $K'_{T_{\text{min}}}$ for preselected e+jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.
FIG. 35: Data/Monte Carlo comparison for $H_T$ for preselected $e+$jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

FIG. 36: Data/Monte Carlo comparison for HITFIT $\chi^2$ for preselected $e+$jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.
FIG. 37: Data/Monte Carlo comparison for $L_1$ for preselected $e+$-jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

FIG. 38: Data/Monte Carlo comparison for $H_T$ for preselected $e+$-jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.
FIG. 39: Data/Monte Carlo comparison for $E_T$ for preselected $e+$jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

FIG. 40: Data/Monte Carlo comparison for $P_T^e$ (highest) for preselected $e+$jets events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

XII. TEMPLATE PLOTS

The $\cos\theta^*$ templates used in the maximum likelihood fit are given in this section, first for the $\mu+$jets channel, then for the $e+$jets channel. The events pass all selection criteria. Following these templates are the $\cos\theta^*$ distributions where the top quark mass, jet energy scale corrections, and Monte Carlo samples are varied.
FIG. 41: Data/Monte Carlo comparison for $P_T^{jet}$ (highest) for preselected $e+\text{jets}$ events. The left figure shows the individual $t\bar{t}$, $Wjjjj$ and QCD contributions from Monte Carlo while the right figure shows the sum of the contributions.

These are the templates for the $\mu+\text{jets}$ and $e+\text{jets}$ channel for $f^+ = 0.0, 0.10, 0.20, \text{and } 0.30$.

FIG. 42: $\cos\theta^*$ distribution for $\mu+\text{jets}$ (left), $e+\text{jets}$ (right) $t\bar{t}$ signal for $f^+ = 0.0, 0.10, 0.20, 0.30$
These are the individual templates for the $\mu$+jets channel.

**FIG. 43:** $\cos\theta^*$ distribution for $\mu$+jets $t\bar{t}$ signal for $f^+=0.0$

**FIG. 44:** $\cos\theta^*$ distribution for $\mu$+jets $t\bar{t}$ signal for $f^+=0.05$
FIG. 45: $\cos\theta^*$ distribution for $\mu$+jets $t\bar{t}$ signal for $f^+=0.10$

FIG. 46: $\cos\theta^*$ distribution for $\mu$+jets $t\bar{t}$ signal for $f^+=0.15$
FIG. 47: \( \cos \theta^* \) distribution for \( \mu^+ \) jets \( t\bar{t} \) signal for \( f^+ = 0.20 \)

FIG. 48: \( \cos \theta^* \) distribution for \( \mu^+ \) jets \( t\bar{t} \) signal for \( f^+ = 0.25 \)
FIG. 49: $\cos\theta^*$ distribution for $\mu$+jets $t\bar{t}$ signal for $f^+ = 0.30$

FIG. 50: $\cos\theta^*$ distribution for $Wjjjj$ background in the $\mu$+jets channel
FIG. 51: $\cos \theta^*$ distribution for QCD background in the $\mu +$ jets channel
These are the individual templates for the $e$+jets channel.

**FIG. 52:** $\cos\theta^*$ distribution for $e$+jets $t\bar{t}$ signal for $f^+=0.0$

**FIG. 53:** $\cos\theta^*$ distribution for $e$+jets $t\bar{t}$ signal for $f^+=0.05$
FIG. 54: $\cos\theta^*$ distribution for $e+\text{jets} t\bar{t}$ signal for $f^+=0.10$

FIG. 55: $\cos\theta^*$ distribution for $e+\text{jets} t\bar{t}$ signal for $f^+=0.15$
FIG. 56: $\cos\theta^{*}$ distribution for $e+\text{jets}\, t\bar{t}$ signal for $f^{+}=0.20$

FIG. 57: $\cos\theta^{*}$ distribution for $e+\text{jets}\, t\bar{t}$ signal for $f^{+}=0.25$
FIG. 58: $\cos\theta^*$ distribution for $e\pm$ jets $t\bar{t}$ signal for $f^+=0.30$

FIG. 59: $\cos\theta^*$ distribution for $Wjjjj$ background in the $e\pm$-jets channel
FIG. 60: $\cos \theta^*$ distribution for QCD background in the $e+\text{jets}$ channel
These are the templates for 3 different top quark masses in the $\mu+$jets and $e+$jets channel.

FIG. 61: $\cos\theta^*$ distribution for $m_t = 170, 175, \text{and } 180$ GeV for $\mu+\text{jets}$ $t\bar{t}$ signal

FIG. 62: $\cos\theta^*$ distribution for $m_e = 170, 175, \text{and } 180$ GeV for $e+\text{jets}$ $t\bar{t}$ signal
These are the templates for $\mu$+jets and $e$+jets ttbar signal with jet energy scale correction variations of $+1 \sigma$, $-1 \sigma$, and nominal. Templates for both $f^+=0.0$ and $f^+=0.30$ are shown.

FIG. 63: $\cos \theta^*$ distribution for jet energy scale correction variations of $+1 \sigma$, $-1 \sigma$, and nominal for $\mu$+jets $t\bar{t}$ signal for $f^+=0.0$ and 0.30

FIG. 64: $\cos \theta^*$ distribution for jet energy scale correction variations of $+1 \sigma$, $-1 \sigma$, and nominal for $e$+jets $t\bar{t}$ signal for $f^+=0.0$ and 0.30
These are the templates for the different $Wjjjj$ background models in the $\mu+$jets and $e+$jets channel.

FIG. 65: $\cos\theta^*$ distribution in the $\mu+$jets channel for $Wjjjj$ models Higgs Tune A and iqopt10

FIG. 66: $\cos\theta^*$ distribution in the $e+$jets channel for $Wjjjj$ models Higgs Tune A and iqopt10

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[8] Internal/EB from the DØ Top Group Home page DØ Top Analysis and Data Sample for the Winter Conferences 2004 v0.3.
[9] Internal/EB from the DØ Top Group Home page Measurement of the t¢t Production Cross Section at $\sqrt{s} = 1.96$ TeV in the Lepton Plus Jets Final States Using a Topological Method v0.5.
[10] Internal/EB from the DØ Top Group Home page Direct Measurement of the Top Quark Mass in the Lepton Plus Jets Channel Using Run II Data v0.1.
[13] Internal/EB from the DØ Top Group Home page Measurement of the W Helicity in t¢t Decays at $\sqrt{s} = 1.96$ TeV in the Lepton + Jets Final States Using a Lifetime Tag v1.4.