Measurement of W Boson Helicity in Top Quark Decay

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Meeting of the Division of Particles and Fields of the American Physical Society
August 12, 2011
Brown University, Providence, Rhode Island
OUTLINE

- Introduction
- Analysis
- Conclusion
Start with answering some basic questions

- What is W boson helicity?
- Why in top quark decay?
- How do we measure that?
The top quark is the most recently discovered quark, discovered at Fermilab in 1995.

Top quark pair production at Tevatron

$q \bar{q}$ annihilation (85%)
gluon fusion (15%)

Top quark decays ~100% to W and b quark
What is W boson Helicity?

The $W$ boson from top quark decay is produced in one of three polarization states:

- **Negative helicity** $f_- \sim 30\%$ (left handed, $W_-$)
- **Zero helicity** $f_0 \sim 70\%$ (longitudinal, $W_0$)
- **Positive helicity** $f_+ \sim 0\%$ (right handed, $W_+$)

In Standard Model:

The uncertainties in the Standard Model prediction are far smaller than the precision we can achieve experimentally. Any significant deviation from the SM values would be a clear signature of new physics.
How do we measure $W$ Helicity

We can get $W$ helicity fractions ($f_0$ and $f_+$) from the $\cos \theta^*$ distribution in $W$ rest frame.

$$c = \cos \theta^* = \frac{-(\vec{l} \cdot \vec{b})}{\vec{l} \cdot \vec{b}}$$

This is the basis of this measurement.

$$\omega(c) \propto 2(1 - c^2)f_0 + (1 - c)^2f_- + (1 + c)^2f_+$$
Identify DATA sample and model signal and background

Event Selection

Reconstruct $\cos \theta^*$ for selected events

Measure $W$ helicity fraction
Identify DATA sample and model signal and background

Event Selection

Reconstruct $\cos^\theta*$ for selected events

Measure W helicity fraction
Data used for this analysis was collected between April 2002 and June 2009 which corresponds to a total integrated luminosity of 5.4 fb$^{-1}$.

Simulated samples (Monte Carlo) were used to model the data.
Signal Events for this analysis

$\ell + \text{jets: } \ell \nu \geq 4 \text{jets}$

$\bar{t}t \rightarrow WbWb \rightarrow \ell v bb jj$

$\ell \nu \ell' \nu' \geq 2 \text{jets}$

$\bar{t}t \rightarrow WbWb \rightarrow \ell \ell' vv' bb$

Missing $E_T$

$b$ jet

$q$ jet

$q$ jet

$b$ jet

$e$ or $\mu$

$e$ or $\mu$

$e$ or $\mu$

$e$ or $\mu$
Background events for this analysis

There are two categories of background

1. Inherent background from standard model physics process having similar final state as from top pair, e.g.

\[ W + \geq 4 \text{ jets} \rightarrow \ell \nu + \geq 4 \text{ jets} \]

Simulated sample (MC) used to model the inherent background

2. Instrumental background where a final state object is misidentified, e.g. a jet misidentified as an electron.

Data control sample is used to model the instrumental background
Identify DATA sample and model signal and background

Event Selection

Reconstruct $\cos \theta^*$ for selected events

Measure W helicity fraction
The event selection is done in two steps

**Pre-selection**

Apply well understood selection criteria to identify each object expected in the final state of an event with top pair.

**Example : for lepton+jet final state, we select events with**

- At least 4 or more jets with a minimum transverse momentum
- 1 well identified lepton (electron or muon)
- Missing energy to account for the neutrino
Final Selection

- Use a multivariate discriminant to separate background from signal events and apply a cut to get a sample enriched with top quarks.

- We develop a classical likelihood ($L_t$) based on simulated events that combines all the information we have in terms of several variables. An example of one such variable:

  $H_T$ – Scalar sum of the pre-selected jet transverse momentum. Jets originating from background are less energetic than those originating from top pair decay.

  $H_T$ distribution of signal (red), background and data (points) after pre-selection.
Optimization of final selection

- Over 10 such variables are used to train the classical likelihood where different combinations of these variables return one classical likelihood.

- Optimization is done by trying all possible combinations of variables, and all possible cut points on the likelihood, to find the one that maximizes the figure of merit (Signal/Background).
One Example ......

Electron + Jets final state
One Example ......

Electron + Jet final state

Remove these events
For each of the 5 channels, we get one such optimized likelihood

We apply the optimized selection criteria

<table>
<thead>
<tr>
<th>Final State</th>
<th>Electron + JETS</th>
<th>Muon + JETS</th>
<th>Electron + Electron</th>
<th>Muon + Muon</th>
<th>Electron + Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal purity before $L_t$ cut (PRE-SELECTED SAMPLE)</td>
<td>41%</td>
<td>49%</td>
<td>2%</td>
<td>2%</td>
<td>55%</td>
</tr>
<tr>
<td>Signal Purity after $L_t$ cut (FINAL SAMPLE)</td>
<td>73%</td>
<td>71%</td>
<td>83%</td>
<td>65%</td>
<td>82%</td>
</tr>
</tbody>
</table>

This defines the top quark sample used for our measurement
Identify DATA sample and model signal and background

Event Selection

Reconstruct $\cos \theta^*$ for selected events

Measure W helicity fraction
For each event in the final sample we reconstruct the four-momenta of the top quark and the W boson. For each event, we calculate $2 \cos \theta^*$ (one for each $tWb$ vertex).

This is done using the following constraints:

- The invariant mass of the lepton and neutrino is the $W$ mass
- In lepton+jet events, the invariant mass of the two jets is the $W$ mass
- The top mass is 172.5 GeV

Using these four-momenta, $\cos \theta^*$ is calculated
Identify DATA sample and model signal and background

Event Selection

Reconstruct $\cos \theta^*$ for selected events

Measure $W$ helicity fractions
Starting with the simulated signal samples (top pair sample), we model the expected distributions of \( \cos \theta^* \) for left-handed, longitudinal and right-handed \( W \)s. Once we have the \( \cos \theta^* \) distributions for signal, background and data, we use a maximum likelihood fit, for the data to be consistent with the sum of signal and background in the \( \cos \theta^* \) distribution.

The fit parameters include the \( W \) helicity fractions \( f_0 \) and \( f_+ \).
lepton+jet final state
(hadronic W boson decay)

Di-lepton final state
RESULT

Analyzing a data sample corresponding to $5.4 \text{ fb}^{-1}$ of proton-antiproton collisions collected by the D0 detector at Fermilab

\[ f_0 = 0.669 \pm 0.102 [\pm 0.078(\text{stat.}) \pm 0.065(\text{syst.})] \]
\[ f_+ = 0.023 \pm 0.053 [\pm 0.041(\text{stat.}) \pm 0.034(\text{syst.})] \]

Compare to SM values: $f_0 = 0.698$ & $f_+ = 4.1 \times 10^{-4}$

The consistency of this result with the standard model value is 98%
The ellipses are the 68\% and 95\% C.L. contours, the triangle borders the physically allowed region where $f_0$ and $f_+$ sum to one or less, and the star denotes the SM values.
CONCLUSION

After analyzing 5.4 fb$^{-1}$ of data collected with the D0 detector, we find the measured values of the W helicity fractions consistent with the standard model value.

**Hence we state that we found no evidence of new physics at the tWb decay vertex.**

This is the world's most precise measurement of W boson helicity published in PRD [Phys. Rev. D 83, 032009 (2011)]
THANK YOU