Testing SM in Top Quark Decays

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for the CDF and DØ collaborations

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Introduction

The Top Quark

- Discovered by CDF and DØ in 1995.
- Completes set of quarks in SM.
- Quantum numbers as for up-type quarks.
- Production and decay properties fully determined within SM.
- Mass is the only free parameter.

Only few of its predicted properties verified
The $p\bar{p}$ Accelerator Tevatron

- Circumference 7 km.
- $p\bar{p}$ collisions
- Run I (1987-1995)
- Run II (since 2001)
  Collision energy 2 TeV
- 2 experiments, CDF and DØ, record events.
  $\mathcal{L} > 1 \text{ fb}^{-1}$ on tape.
Top Production & Decay Channels

Strong production mechanism.
Electroweak production (single top) covered by W. Wagner

- Top quarks produced in pairs
- In SM top quark decays to $bW$ (~ 100%).
  Can this be verified? Does it show expected properties?

- Decay modes are defined by $W$-decays:
  - Dilepton $(2b + 2l + 2\nu)$
  - Lepton+jets $(2b + 2q + l\nu)$
  - Alljets $(2b + 4q)$

Cleanest channel: Dilepton.
Golden channel: Lepton+jets.
**W-Helicity in Top Decays**

Does the top decay show the expected spin structure?

SM: only lefthanded particle couple to $W$s ($V-A$ coupling), $W$ is lefthanded or longitudinal.

- **Longitudinal $W$**
  - SM: $f_0 = 70\%$

- **Left-handed $W$**
  - SM: $f_- = 30\%$

- **Right-handed $W$**
  - SM: suppressed ($f_+ \approx 0$)

In $W$-restframe lepton from $W$ stays (preferably)

- orthogonal to $b$
- along $b$-direction
- opposite to $b$-direction

An admixture of $V+A$ wouldn’t change longitudinal contribution.

Daniel Wicke, Testing SM in Top Quark Decays, W-Helicity in Top Decays

Sensitive Observables

Lepton transvers momentum, $p_{T}^{\text{lept}}$
SM suppresses leptons against $W$ direction
no ambiguities

Lepton-\(b\)-quark inv. mass, $M_{lb}^2$
Uses $b$ and $l$ 4-vectors only.

Angular distributions, $\cos \theta^*$:
Angle $\theta$ between lepton and direction from where the top came in $W$ restframe.
Full reconstruction of $t\bar{t}$ kinematics
Uses $t$, $W$ and $l$ 4-vectors.
**CDF Results using $M_{lb}^2$**

Dilepton and $l+\text{jets}$ on 695 to 750 pb$^{-1}$

- Single and double $b$-tag separately
- One measurement per event
- Compares rec. $M_{lb}^2$ to $V \pm A$ templates

**Dilepton**

- Veto against $Z \rightarrow ll$
- Use 2 assignments
  - $\times$ 2 measurements per event
- Compares rec. $M_{lb}^2$ to templates

**Combined result**

\[ f_+ = -0.02 \pm 0.07 \]
\[ f_+ < 0.09 \quad 95\% \text{CL} \]
**DØ Results using cos θ**

Dilepton and l+jets channel with $\sim 370 \text{ pb}^{-1}$.

**l+jets channel**
- Compares rec. $\cos \theta^*$ to $V \pm A$ templates

**Dilepton channel**
- Special difficulty: find $W$ restframe.
- Assumes $m_t$; use all 4 solutions.
- Repeat reconstruction with smeared momenta 100 times to account detector resolution.

**Combined results (assuming SM $f_0 = 0.7$)**

\[ f_+ = 0.08 \pm 0.08 \pm 0.05 \]

\[ f_+ < 0.24 \quad 95\% \text{CL} \]
**CDF Results using \( \cos \theta^* \)**

Two method in \( l+\text{jets} \) channel with \( \sim 1 \text{ fb}^{-1} \):

**Template based**

Compares rec. \( \cos \theta^* \) to templates \( l+4\text{jets} \) using “best” \( \chi^2 \) assignment.

**Unfolded \( \cos \theta^* \)**

Unfold w/ migration matrix, compare to theory \( l+4 \) or more jets using all assignments; weighed.

**Results obtained assuming SM \( f_0 \) \( (f_0 = 0.7): \)**

\[
\begin{align*}
  f_+ &= -0.05 \pm 0.06 \pm 0.03 \\
  f_+ &< 0.11 \quad 95\%\text{CL}
\end{align*}
\]

**Results obtained assuming SM \( f_+ \) \( (f_+ = 0): \)**

\[
\begin{align*}
  f_0 &= 0.606 \pm 0.12 \pm 0.06 \\
  f_0 &= 0.59 \pm 0.12 \pm 0.07
\end{align*}
\]
Top Quarks Electrical Charge

Do objects used to reconstruct tops add up to the expected charge?

Requires reconstruction of:

- $W$ charge $\rightarrow$ lepton charge
- $b$-quark charge $\rightarrow$ jet charge (more involved)
Jet charge

Sum charge of tracks in $b$-jet

- Errors from in- and out-of-cone tracks
- Statistical method
- Weighting with $p_T$ helps

$$Q_{\text{jet}} := \frac{\sum q_i \cdot p_{T_i}^{0.6}}{\sum p_{T_i}^{0.6}}$$

Calibration

- Using double (vertex) tagged $b\bar{b}$ dijets w/ soft $\mu$ ($\Delta \phi \leq 3.0$)
- Soft $\mu$ determines $b$ charge, $Q_{\text{Jet}}$ calibrated on opposite jet.
- Disentangle $b$, $\bar{b}$, $c$, $\bar{c}$ contributions to obtain pure $b$-jet $Q_{\text{Jet}}$ distribution
Top Quark Charge Analysis

- Need to assign $b$-jet to right top
  Choose best fit to top hypothesis
- Combine lepton and $b$-jet charge to top charge
  (leptonic and hadronic side):

\begin{align*}
Q_{\text{lep}} &= |q_t + q_b| \\
Q_{\text{had}} &= |-q_t + q_b|
\end{align*}

- Templates generated from standard model MC.
  Exotic case by permuting jet charge.

**DØ Result (370 pb$^{-1}$)**

Unbinned likelihood ratio also accounting for remaining background yields

$$|q_{\text{top}}| = \frac{4e}{3}$$

excluded at 94% CL.
Flavour of Top Decay: $V_{tb}$

Deviation from SM prediction $|V_{tb}| \simeq 0.999$, $BR(t \to bW) \simeq 100\%$?

Various SM extensions allow for $|V_{tb}| \ll 1$

Investigate ratio of 0, 1 and 2 $b$-tagged top events to infer

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

CDF expected fractions as function of $R \cdot \epsilon_{b-tag}$

Daniel Wicke, Testing SM in Top Quark Decays, Flavour of Top Decay: $V_{tb}$
**DØ Analysis**

$l+$jets channel using $230 \text{ pb}^{-1}$.

- Measure $R$ and $N_{tt\bar{t}}$ simultaneously.
- Tagging probabilities for different jet types required (obtained separately)
- Use kinematic discriminant in 0 $b$-tag sample to improve separation of signal and background.
- Binned max. likelihood to fit $R$ and $N_{tt\bar{t}}$.
Results

**DØ (230 pb⁻¹)**

$l+$jets

\[
R = 1.03^{+0.19}_{-0.17} \\
R > 0.64 \quad 95\% \text{ CL} \\
|V_{tb}| > 0.80 \quad 95\% \text{ CL}
\]

**CDF (162 pb⁻¹)**

$l+$jets and dilepton

\[
R = 1.12^{+0.27}_{-0.23} \\
R > 0.62 \quad 95\% \text{ CL} \\
|V_{tb}| > 0.78 \quad 95\% \text{ CL}
\]

Conversion assumes

\[|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1\]

A long way to SM \(|V_{tb}| \approx 0.999\)

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Daniel Wicke, Testing SM in Top Quark Decays, Flavour of Top Decay: \(V_{tb}\)

Further Results

Many other tests of the SM in top decay have been performed:

**H⁺ in top decays**
Investigate decays of top events
Limits on BR$(t \to bH^+)$ set for various $H^+$ decay modes and masses.

**$t'$ search**
Check reconstructed top mass distribution
CDF: $760 \text{ pb}^{-1}$: $M_{t'} > 258$ GeV at 95% CL

**$tt'$ Resonance**
Investigate $m_{tt'}$-distribution.
CDF and DØ: Compatible with SM.

CDF: $680 \text{ pb}^{-1}$: $M_{Z'} > 725$ GeV at 95% CL
for $\Gamma(Z') = 1.2\%M_{Z'}$. 
Summary

- Testing SM in top decay is gaining more and more interest.
- **$W$-Helicity**: No hint for an admixture of $V + A$
  
  $CDF (\ 1 \text{fb}^{-1})$: $f_+ < 0.09 (95\% \text{ CL})$

- **Electrical Charge**: Exotic charge value disfavoured
  
  $DØ (370 \text{ pb}^{-1})$: $4e/3$ excluded at 94\% CL

- **Decay Flavour**:
  
  $DØ (230 \text{ pb}^{-1})$: $R > 0.64 (95\% \text{ CL})$

- Several additional searches for deviations available.

*No significant deviations from Standard Model observed (yet).*