Top quark properties at the Tevatron

Summary

◆ Branching ratios and tests of the SM
◆ Searches for non-standard top decays
◆ Anomalous kinematics
◆ W helicity and spin correlations
◆ Resonance production
◆ Conclusions and outlook
Top quark properties overview

* Heaviest known particle: \( m_t = 178.0 \pm 4.3 \text{ GeV}/c^2 \)
  * Sensitive probe for new physics, FCNCs?
  * \( m_t \sim v/\sqrt{2}, \lambda_t \sim 1 \) Related to EWSB?

* Decays as a free quark: \( \tau_t = 5 \times 10^{-25} \text{ s} \ll \Lambda_{QCD}^{-1} \)
  * Spin information is passed to its decay products
  * Test \( V-A \) structure of the SM

* We have not yet measured its spin, charge or width

Single top production offers direct access to \( V_{tb} \)

\[ \sigma_s = 0.88 \text{ pb} \]

\[ \sigma_t = 1.98 \text{ pb} \]
\( \mathcal{B}(t \rightarrow Wb) \) measurement

* \[ R = \frac{\mathcal{B}(t \rightarrow Wb)}{\mathcal{B}(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{ts}|^2 + |V_{td}|^2 + |V_{tb}|^2} \approx 1 \text{ in the SM} \]

* Test assumption \( \mathcal{B}(t \rightarrow Wb) = 1 \), provide indirect measurement on \( |V_{tb}| \)

* Ratio of single to double-tagged events is sensitive to \( b = \mathcal{B}(t \rightarrow Wb) \) and \( \varepsilon = \text{tagging efficiency} \):

\[
N_0 \propto (1 - b\varepsilon)^2, \quad N_1 \propto 2b\varepsilon(1 - b\varepsilon) \text{ and } N_2 \propto (b\varepsilon)^2
\]

\[
b\varepsilon = \frac{2}{N_1/N_2 + 2} = \frac{1}{2N_0/N_1 + 1}
\]

* Always measure the product \( b\varepsilon \). Assume \( \varepsilon \) and extract \( b \)

* CDF uses \( \ell + \text{jets} \) sample \((108 \text{ pb}^{-1})\) and SVX tagging:

<table>
<thead>
<tr>
<th></th>
<th>3-jet</th>
<th>( \geq 4\text{-jet} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-tag events</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>2-tag events</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

* Main backgrounds are \( Wb\bar{b} \), mistags, single top \( s \)--channel and diboson

* Use likelihood to obtain \( b\varepsilon \) most consistent with single and double-tagged events in data. Total number of \( tt \) also fitted.
CDF $B(t \rightarrow Wb)$ results

Most likely value: $b\varepsilon = 0.25^{+0.22}_{-0.18}$ \Rightarrow \boxed{b = 0.54^{+0.49}_{-0.39}} \Rightarrow b > 0.12$ @ 95\% C.L.

Assume $\varepsilon = 0.45 \pm 0.045$ from measurements in calibration samples

CDF Run I: $b = 0.94^{+0.31}_{-0.24} \Rightarrow V_{tb} = 0.97^{+0.16}_{-0.12}$
Ratio of dilepton to $\ell+\text{jets}$ cross sections

* $\sigma_{t\bar{t}\rightarrow\ell\ell} \text{ should be equal to } \sigma_{t\bar{t}\rightarrow\ell+\text{jets}} \text{ if } \mathcal{B}(t \rightarrow Wb) = 100%$

* Therefore $R_\sigma = \frac{\sigma_{\ell\ell}}{\sigma_{\ell+\text{jets}}} = 1$ in the SM

Any deviation would imply non-zero $\mathcal{B}(t \rightarrow Xb)$: sensitive to non-SM decays of top

* By taking the ratio: cancel systematic uncertainties, independent of theoretical $\sigma$ (i.e. PDF’s, $m_t$)

* Create probability distribution for $R_\sigma$

* CDF results using dilepton and $\ell+\text{jets}$ samples (126 and 108 pb$^{-1}$):

$$R_\sigma = 1.45^{+0.83}_{-0.55}$$

$$0.46 < R_\sigma < 4.45 \text{ @ 95\% C.L}$$
Rate of top decays to $\tau \nu b$

- Test of lepton universality, search for new physics (2HDM: $t \rightarrow H^+ b \rightarrow \tau^+ \nu b$)
- In MSSM with high $\tan \beta$, $t \rightarrow H^+ b$ may dominate over $t \rightarrow W^+ b$
- Look for excess over the SM: $t \bar{t} \rightarrow W^+ W^- b \bar{b} \rightarrow \tau^+ \tau^- b \bar{b} + E_T$
- One of the taus decays leptonically and the other hadronically

- $\tau$ ID is crucial: CDF used $58 \text{ pb}^{-1}$ of $W \rightarrow \tau \nu$ data and Pythia MC
CDF rate of top decays to $\tau\nu b$: results

* In dilepton sample with e or $\mu$ and $\tau \rightarrow$hadrons (193 pb$^{-1}$)

* Largest background is jets faking taus

* Major uncertainties: MC $t\bar{t}$ acceptance (generator, ISR, FSR) and $\tau$ ID

Expect 2.3 events, Observe: 2 events

Most likely value: $r(\tau) = 0.8$ (SM expectation: $r(\tau) = 1$)

Set limit: $r(\tau) = \frac{B_{\text{meas}}(t\rightarrow\tau\nu b)}{B_{\text{SM}}(t\rightarrow\tau\nu b)} < 5 \times 95\%$ C.L.
CDF search for anomalous kinematics

* Models beyond the SM predict anomalous top $p_T$ spectra
* Same analysis as $\sigma_{\ell\ell}$ measurement (hep-ex/0404036) with 193 pb$^{-1}$
* New technique to isolate subsets of sample which reveal the largest discrepancy looking at four variables: high $E_T$, lepton $p_T$, $\Delta\phi(\ell, E_T)$ or consistency with $\ell\ell$ topology: 

$$T = \int \exp \left[ - \left( \vec{E}_T^{SM} - \vec{E}_T^{obs} \right)^2 / 2\sigma_{\vec{E}_T}^2 \right] d\vec{E}_T^{SM}$$

* Algorithm loops over different subsamples and creates a multi-variate KS test shape to compare to the SM distribution
* Extract significance of discrepancy (P-value) by pseudoexperiments

Control sample for simulation of kinematics: $W+\geq3$ jets and $W+4$ jets samples
CDF search for anomalous kinematics: results

Consistency with the SM for the whole dilepton sample:

\[ \text{P-value} = 1.0 - 4.5\% \]

The discrepancy arises from an excess of events with low \( p_T \) leptons compared to SM expectation.
* In the SM only left-handed $W_-$ and longitudinal $W_0$ may be produced

* $W_0$ fraction: $F_0 = \frac{\Gamma(W_0)}{\Gamma(W_0) + \Gamma(W^\pm)} = \frac{1}{1 + 2(M_W/M_t)^2} \approx 0.7 \Rightarrow F_+ \approx 0.3$

* Any V+A structure in the dynamics would yield $F_+ \neq 0$ and $F_- \leq 0.3$

* We can estimate the helicity content by fitting templates of $\cos \phi$

$\phi$: angle between the $\ell$ and the $b$ in W rest frame
Lepton $p_T$ spectra for different W helicities

- The $W_-$ lepton is emitted antiparallel to the W boost
- The $W_0$ lepton is emitted perpendicular to the W boost
- $W_0$ lepton spectrum is harder than $W_-$
- We can estimate the helicity content of $t\bar{t}$ samples by analyzing their $\ell$ $p_T$ spectra
CDF W helicity measurement

* Use dilepton and $\ell+\text{jets}$ samples: $162-192 \text{ pb}^{-1}$

* Analysis with Secondary Vertex Tagger:

<table>
<thead>
<tr>
<th>sample</th>
<th>dilepton</th>
<th>$\ell+\text{jets}$</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td># leptons</td>
<td>26</td>
<td>57</td>
<td>83</td>
</tr>
</tbody>
</table>

* Construct likelihood function with the PDFs of $p_T$ of leptons from background and signal for different helicities:

$$L = G(\beta; \mu, \sigma) \prod_{i=1}^{N} (\beta P(x_i, \text{bkg}) + (1 - \beta)[F_0 P(x_i; 0) + (1 - F_0) P(x_i; -1)])$$

$\beta$: background fraction  
$G(\beta; \mu, \sigma)$: Gaussian constrain on $\beta$ with $\mu \pm \sigma$ prior estimate  
$N$: number of reconstructed leptons  
$P(x_i, \text{bkg})$: PDF of charged $\ell$ with $p_T = x_i$ due to background process  
$P(x_i, h)$: PDF of charged $\ell$ with $p_T = x_i$ from W with helicity $h$

* Major systematic uncertainties: top mass and background normalization
CDF W helicity measurement: distributions

dilepton

CDF II preliminary
\[ \int L dt = 200 \text{ pb}^{-1} \]

\begin{itemize}
  \item data
  \begin{itemize}
    \item tt
    \item Drell-Yan
    \item lepton fakes
    \item WW/WZ
    \item Z \rightarrow \tau \tau
  \end{itemize}
\end{itemize}

\begin{align*}
  \hat{F}_0 &= -0.54 \\
  F_0 &< 0.52 @ 95\% \text{C.L.}
\end{align*}

\[ F_0 = 0.88^{+0.12}_{-0.47}, \quad F_0 < 0.88 @ 95\% \text{C.L.} \]

\[ \int L dt = 162 \text{ pb}^{-1} \]

\begin{itemize}
  \item data
    \begin{itemize}
      \item tt
      \item WW, WZ
      \item single top
      \item Wc
      \item Wc\bar{c}
      \item Wb\bar{b}
      \item QCD
      \item mistags
    \end{itemize}
\end{itemize}

\[ F_0 = 0.88^{+0.12}_{-0.47}, \quad F_0 < 0.88 @ 95\% \text{C.L.} \]

\[ \int L dt = 200 \text{ pb}^{-1} \]

\[ \int L dt = 162 \text{ pb}^{-1} \]
Combining the samples:

\[ F_0 = 0.27^{+0.35}_{-0.21} \text{(stat + syst)} \]

\[ F_0 < 0.88 @ 95\% \text{C.L.} \]

* The data distribution for dileptons is softer than any signal or background component → the longitudinal component is forced negative

* 2\(\sigma\) level discrepancy for \(F_0\) in the dilepton channel

* The combined result is compatible with the SM at 1\(\sigma\)
W helicity: Matrix Element Method

Likelihood method to extract top properties with maximal use of statistical information:

\[ P(x; \alpha) = Acc(x) \times \frac{1}{\sigma} \int d^n\sigma(y; \alpha) dq_1 dq_2 f(q_1) f(q_2) W(x, y) \]

- \( x \) set of reconstructed variables measured in the detector
- \( \alpha \) parameter to estimate, for the helicity calculation \( \alpha = F_0 \)
- \( d^n\sigma \) differential cross section (L0 matrix element \( \rightarrow \) cut on \( N_{\text{jets}} = 4 \))
- \( f(q) \) parton distribution function
- \( W(x, y) \) transfer function: probability that a parton level set of variables \( y \) appears as \( x \) in the detector
- Integrate over all possible set of parton variables \( y \) to observe \( x \)

\[-\ln L(\alpha) = -\sum_{i=1}^{N} \ln \left[ c_1 P_{t\bar{t}}(x_i; \alpha) + c_2 P_{\text{bkg}}(x_i) \right] + N \int Acc(x) \left[ c_1 P_{t\bar{t}}(x; \alpha) + c_2 P_{\text{bkg}}(x) \right] dx\]

Obtain best values of \( F_0 \) and the signal and background fractions (\( c_1 \) and \( c_2 \)) by minimizing \(-\ln L(F_0)\)
Based on the Matrix Element $\ell+\text{jets}$ mass analysis of Run I data ($125 \text{ pb}^{-1}$)

* Include all 12 possible combinations of jets plus all possible neutrino $p_z$ to form the top
* Construct background and signal probabilities for each event
* Well measured events contribute more information than poorly measured events
* Better discrimination between signal and background: better mass measurement to date!

* Statistics limited: only 22 events after final selection!

\[
F_0 = 0.56 \pm 0.31 (\text{stat} + m_t) \pm 0.07 (\text{syst})
\]

(submitted to PRL, hep-ex/0404040)

\[
F_0 = 0.91 \pm 0.39 (\text{stat} + \text{syst})
\]

(CDF Run I Result)
Using $\ell+\text{jets}$ sample (160 pb$^{-1}$)

Developing two parallel analysis: topological selection / $b$-tagging and then event kinematic fitting

The data is fitted to $\cos \phi$ templates for various $F_+$ fixing $F_0 = 0.7$

Simultaneous determination of $F_+$ and S/B ratios

Working on optimization and combination of analyses

Expect results for ICHEP
DØ Run I spin correlations

* Confirm that top decays before spin flips, lower limit on $\tau_t \Rightarrow$ lower limit on $\Gamma_t$

* Non standard EW interactions may manifest in decay product anomalies

* Dilepton analysis (125 pb$^{-1}$) Phys. Rev. Lett. 85, 256, 2000

* At the Tevatron, the better spin-basis is the “off-diagonal”, where like-spin rate vanishes to LO: defined by $\tan \psi = \frac{\beta^2 \sin \theta^* \cos \theta^*}{1 - \beta^2 \sin^2 \theta^*}$

* $3C$ fit $+ m_t = 175 \text{ GeV}/c^2$ and weight each of the four neutrino solutions, use two-dimensional binned likelihood $(\cos \theta_+, \cos \theta_-)$

\[ \kappa > -0.28 \ @ \ 68\% \text{C.L.} \] (SM: $\kappa = 0.88$)

Differential production: $\frac{1}{\sigma} \frac{d^2 \sigma}{d \cos \theta_- \cos \theta_+} = \frac{1 + \kappa \cos \theta_- \cos \theta_+}{4}$
DØ Run I search for $t\bar{t}$ resonances

* Technicolor may provide another EWSB mechanism

* Look for narrow resonances (compared to detector resolution) of a heavy top quark condensate $X \rightarrow t\bar{t}$ or $Z' \rightarrow t\bar{t}$

* Use Run I mass $\ell$+jets sample (130 pb$^{-1}$) and analysis

* Perform 3C kinematic fit over two orthogonal analyses: topological cuts and soft muon tagging

A total of 41 events:

<table>
<thead>
<tr>
<th>e+jets</th>
<th>$\mu$+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>e+jets/SLT</th>
<th>$\mu$+jets/SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

* Main systematic uncertainties: MC acceptance (ISR/FSR, PDF) and Jet Energy Scale
**DØ Run I search for $t\bar{t}$ resonances: results**

<table>
<thead>
<tr>
<th>data</th>
<th>$X \rightarrow t\bar{t}$</th>
<th>SM $t\bar{t}$</th>
<th>W+jets &amp; QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>4.2 ± 3.2</td>
<td>23.7 ± 11.6</td>
<td>15.4 ± 10.6</td>
</tr>
</tbody>
</table>

Set limit with Bayesian statistics: fit data $m_{t\bar{t}}$ distribution to weighted sum of three distributions $X \rightarrow t\bar{t}$, SM $t\bar{t}$ and W+jets & QCD.

Assuming $\Gamma_X = 0.012M_X$, $m_t = 175$ GeV/c$^2$ and flat priors, exclude narrow leptophobic X boson: $M_X > 560$ GeV/c$^2$ \(\text{(accepted by PRL, hep-ex/0307079)}\)

$M_X > 480$ GeV/c$^2$ \(\text{(CDF Run I: PRL 85, 256, 2000)}\)
Anomalous couplings

* New physics may appear in altered rates of FCNC
* At the Tevatron, can look for $t \rightarrow qZ$ and $t \rightarrow q\gamma$ where $q = u, c$ are expected to be extremely rare
* Study the decay instead of the production, normalize to $N_{t \bar{t}}$ produced

![Graph showing exclusion region for $\kappa_{tu\gamma}$ and $V_{tuZ}$](image-url)
Conclusions and outlook

➤ The Tevatron is performing very well, providing lots of new data

➤ Top quark physics is an excellent probe of the SM and a window beyond

➤ First Run II results with similar or exceeding luminosity to Run I

➤ Very sophisticated new analysis techniques are in place, ready to crunch more data and surpass Run I sensitivity

➤ Many exciting physics results from top properties!

CDF and DØ combined expected precisions for $2 fb^{-1}$:

- $W$ helicity $F_0$, $F_+$: 0.09, 0.03

- $R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)}$: 4.5%

- $|V_{tb}|$ from R: $> 0.25$

- $B(t \rightarrow \gamma q)$: $2 \times 10^{-3}$

- $\sigma$ single top: 20%

- $\Gamma_t$ from single top: 25%

- $|V_{tb}|$ from single top: 12%

- $B(t \rightarrow qZ)$: 0.02