Top Quark Physics

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The Top Quark in the SM and Beyond

- All top quark properties (except its mass) are fixed in the SM
  - It’s just another isospin $+\frac{1}{2}$ quark
- In addition, we also know that $|V_{tb}| \approx 1$
  - So the top has one dominant decay mode: $t \rightarrow Wb$
- Most of the interest in top quark physics comes from the potential to find non-standard effects
- Is Yukawa coupling a hint?

Top is the only fermion with a “natural” coupling
What We Can Learn From the Top Quark

• Questions

• Measurements in this talk
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  - What is the Higgs boson mass?
  - Do we understand heavy flavor production in QCD?
  - Are there more than three fermion generations?
  - Are there new massive particles?
  - Are there charged Higgs bosons?
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- **Measurements in this talk**
  - Single top cross section
  - Searches for $H^+$ and $W'\rightarrow tb, t\rightarrow H^+b$
  - Search for FCNC
  - Top quark pair cross section
  - Top quark mass
  - Top quark charge
  - Forward-backward charge asymmetry
  - $M_{tt}$ distribution
  - $W$ boson helicity
  - Top quark branching fractions
  - Search for $t'$ quark
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Top Quark Signatures

- Single top quark:
  - Dominant backgrounds arise from vector boson + jet production
  - Good $b$ jet and lepton ID, missing $E_T$ resolution help in finding top quarks

- Top quark pair:

Top Quarks, One at a Time

- Production at the Tevatron:
  - Direct access to the $tWb$ coupling
    - overall rate and ratio between s- and t-channels are sensitive to new physics
  - Experimental challenge:
    - cross section $\sim x2$ lower than $t\bar{t}$
    - large backgrounds from $W + 2\text{jet}$ $\sigma_{Wjj} \approx 19,000 \text{ pb}$
  - Need multivariate selection techniques to extract signal

- s-channel
  - $0.88 \text{ pb}$

- t-channel
  - $1.98 \text{ pb}$
Multivariate Methods

Goal: Given a set of measurements $\mathbf{x}$, find

$$p(S|\mathbf{x}) = \frac{p(S)p(\mathbf{x}|S)}{p(S)p(\mathbf{x}|S) + p(B)p(\mathbf{x}|B)}$$

Neural network

- **Input**
- **Output**
- Train on MC samples to optimize weights

Decision tree

- Training determines “shape” of tree
- Iterative “boosting” improves performance

Matrix element

- Calculate $p(S|\mathbf{x})$ from signal and bkg differential cross sections
- Integrate over detector resolution

Output

- $p(\mathbf{x}|S)$
- $p(\mathbf{x}|B)$

Input

- $\mathbf{x}$
Single Top Cross Section

- Both CDF and DØ use several multivariate discriminants to find single top candidates. Examples:

**DØ**

- DØ: $\sigma = 4.7 \pm 1.3\, \text{pb}$
  - 3.6σ significance
  - $|V_{tb}| > 0.68\,\text{ at } 95\%\,\text{C.L.}$

**CDF**

- CDF: $\sigma = 2.2 \pm 0.7\, \text{pb}$
  - 3.7σ significance
  - $|V_{tb}| > 0.66\,\text{ at } 95\%\,\text{C.L.}$
Constraints on $Wtb$ Couplings

- Rate and kinematic distributions in single top events depend on the $Wtb$ coupling structure
  - can search for right-handed and/or tensor couplings

$$\mathcal{L} = \frac{g}{\sqrt{2}} W^-_\mu \bar{b}_\gamma^{\mu} \left( f^L_1 P_L + f^R_1 P_R \right) t$$

$$- \frac{g}{\sqrt{2} M_W} \partial^\nu W^-_\mu \bar{b}_\sigma^{\mu\nu} \left( f^L_2 P_L + f^R_2 P_R \right) t + h.c.$$
Search for $W'$

- $W' \rightarrow tb$ leads to the same final state as s-channel single top production
  - use single top selection to search for $W'$
  - signals are enhanced rate and resonance in $M_{Wjj}$

$m_{W'} > 731$ GeV @ 95% C.L

$m_{W'} > 800$ GeV @ 95% C.L
Flavor-Changing Neutral Currents

- FCNC would increase single-top cross section

**CDF:**

\[ \kappa_{gtu} / \Lambda < 0.025 \text{ TeV}^{-1} \]

\[ \kappa_{gtc} / \Lambda < 0.105 \text{ TeV}^{-1} \]

@ 95% C.L.

**H1:**

Anomalous coupling \( \kappa_{tu\gamma} \)

\[ \sigma(ep \rightarrow etX) < 0.16 \text{ pb} \]

@ 95% C.L.
Top Quarks, Two at a Time

- Production at the Tevatron:
- Total cross section: \( \sim 7 \text{ pb} \)

- Top discovery, most properties measurements use \( tt \) events
- CDF has recently measured the \( qq \) and \( gg \) contributions:

  - Based on \( \Delta \phi \) between the leptons in dilepton events:

  \[
  F_{gg} = 0.53^{+0.35+0.07}_{-0.37-0.08}
  \]
Production Cross Section

• The $tt$ cross section has been measured in many final states using kinematic and $b$ tag information independently.

\[ \sigma(pp \rightarrow tt) = 6.xx \pm yy \pm zz \text{ pb} \]
Mass Measurement from Cross Sections

- Assuming that production is governed by SM, can compare measured to calculated cross sections to extract top mass
  
  means that mass is measured in a well-defined renormalization scheme

**NLL+NLL cross section:**
\[ m_t = 167.8 \pm 5.7 \text{ GeV} \]

**Approx NNLO cross section:**
\[ m_t = 169.6 \pm 5.4 \text{ GeV} \]
Top Quark Mass ($\ell + \text{jets}$)

- Goal: measure top mass precisely...
  - to constrain Higgs mass
- ...in as many channels as possible
  - to search for new physics

- Matrix element method provides best sensitivity
- discriminate between top mass hypotheses as well as between signal and background
- calibrate jet energy measurement from $W \rightarrow jj$ in signal events

$\ell + \text{jets}$ modes have optimal combination of rate and background
Top Quark Mass ($\ell$ +jets)

- Results:
- **DØ:**
  
  $m_t = 172.1 \pm 1.1 \pm 1.6$ GeV

- **CDF:**
  
  $m_t = 172.2 \pm 1.0 \pm 1.3$ GeV
Top Quark Mass with Minimal Systematics

- Use observables that vary with top mass but have no first-order dependence on jet response
  - lepton $p_T$
  - $b$ decay length in $xy$ plane

$m_t = 175.3 \pm 6.2 \pm 3.0$ GeV

Dominant systematics will scale with sample size

Currently statistics-limited, but will be an important technique at the LHC
Top Quark Mass (Dilepton)

- Matrix element method can also be applied to dilepton events

- CDF: Matrix Element,NN event selection

- DØ: Matrix Element, $e\mu$ channel

$\begin{align*}
m_t &= 171.2 \pm 2.7 \pm 2.9 \text{ GeV} \\
m_t &= 174.4 \pm 3.2 \pm 2.1 \text{ GeV}
\end{align*}$
Top Quark Mass (all jets)

- Advantages of the all-hadronic channel:
  - largest $tt$ branching fraction
  - fully measured final state
- Disadvantage:
  - huge background from multijet production
- $b$ identification and neural network trained on kinematic differences are used in event selection

$\text{CDF Run II Preliminary (1.9 fb^{-1})}$

$\chi^2 / \text{N dof} = 21.4 / 27$

$\text{Prob} = 0.785$

$m_t = xxx \pm yyy \pm zzz \text{ GeV}$
World Average Top Quark Mass

\[ m_t = 172.4 \pm 0.7 \pm 1.0 \text{ GeV} \]
0.7 % precision

\[ m_H < xxX \text{ GeV} @ 95\% \text{ C.L.} \]
Top Quark Charge

- Have we really observed the top quark, or some new particle with charge 4/3?
- Test by kinematic reconstruction, then measurement of charge of jet paired with the lepton

CDF Run II preliminary, L=1.5 fb⁻¹

CDF

- SM like
- XM like

SM strongly favored

\[ p\text{-value for } +4/3: \, 0.2\% \]

DØ, 370 pb⁻¹

- Data
- \(|q| = 2e/3\)
- \(|q| = 4e/3\)

SM favored

\[ p\text{-value for } +4/3: \, 7.8\% \]
Forward-backward Charge Asymmetry

- In SM, small asymmetry in $y_t - y_{\bar{t}}$ (5-10%) arises from NLO effects
  - new physics might enhance the asymmetry

**CDF**

\[ A_{FB}^{\text{corrected}} = 0.17 \pm 0.07_{\text{stat}} \pm 0.04_{\text{sys}} \]

\[ A_{FB} = 17 \pm 7 \pm 4 \% \]

**DØ**

\[ A_{FB} = 12 \pm 8 \pm 1 \% \]
The $M_{tt}$ Distribution

- Non-SM distribution for $tt$ invariant mass could indicate
  - presence of an $X \rightarrow tt\bar{t}$ resonance
  - interference from non-SM process

$m_{Z'} < 760$ GeV @ 95% C.L.
W Boson Helicity

- In the SM, 70% of W’s from top decay have helicity 0, 30% have helicity -1
- Direct measurements might reveal non-standard couplings

Measurement is based on direct reconstruction of \( \cos \theta^* \)

Detector and acceptance effects accounted for by:
- fit to MC templates or
- bin-by-bin unfolding
$W$ Boson Helicity

- DØ, template method
  - $\ell + \text{jets}$ and $\ell\ell$ channels
  - use both $W$'s in each event

$$f_0 = 0.49 \pm 0.10 \pm 0.08$$
$$f_+ = 0.11 \pm 0.05 \pm 0.05$$
SM $p$-value: 23%

- CDF ($\ell + \text{jets}$ channel)

Combination:
$$f_0 = 0.66 \pm 0.16$$
$$f_+ = -0.03 \pm 0.07$$
Top Quark Branching Fractions

- Use top quark event yields with 0, 1, and 2 $b$-tagged jets to measure production cross section and $R \equiv \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)}$

$$R = 0.97^{+0.09}_{-0.08}$$

$$\sigma_{\bar{t}t} = 8.18^{+0.90}_{-0.84} \pm 0.50 \text{ (lumi) pb}$$
Search for Invisible Decays

- Measure absolute rate (rather than fraction) of events with 2 $b$-tagged jets to determine $B(t \rightarrow X)$
  - sensitive to invisible top decays

<table>
<thead>
<tr>
<th>Sample</th>
<th>2 Jets</th>
<th>3 Jets</th>
<th>4 Jets</th>
<th>≥ 5 Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW$</td>
<td>0.5±0.1</td>
<td>0.5±0.1</td>
<td>0.2±0.0</td>
<td>0.1±0.0</td>
</tr>
<tr>
<td>$WZ$</td>
<td>2.6±0.3</td>
<td>0.8±0.1</td>
<td>0.2±0.0</td>
<td>0.0±0.0</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.1±0.0</td>
<td>0.0±0.0</td>
<td>0.0±0.0</td>
<td>0.0±0.0</td>
</tr>
<tr>
<td>Single Top (s)</td>
<td>8.4±1.2</td>
<td>2.8±0.4</td>
<td>0.7±0.1</td>
<td>0.1±0.0</td>
</tr>
<tr>
<td>Single Top (t)</td>
<td>2.0±0.3</td>
<td>1.8±0.2</td>
<td>0.5±0.1</td>
<td>0.1±0.0</td>
</tr>
<tr>
<td>Z+LF</td>
<td>1.1±0.2</td>
<td>0.7±0.1</td>
<td>0.2±0.0</td>
<td>0.1±0.0</td>
</tr>
<tr>
<td>$Wb\bar{b}$</td>
<td>33.9±13.3</td>
<td>10.6±4.3</td>
<td>2.0±0.9</td>
<td>0.5±0.2</td>
</tr>
<tr>
<td>$Wc\bar{c}$/Wc</td>
<td>6.1±2.5</td>
<td>2.7±1.1</td>
<td>0.7±0.3</td>
<td>0.2±0.1</td>
</tr>
<tr>
<td>Mistags</td>
<td>4.3±1.0</td>
<td>2.6±0.7</td>
<td>0.7±0.2</td>
<td>0.2±0.1</td>
</tr>
<tr>
<td>Non-$W$</td>
<td>2.7±1.9</td>
<td>0.8±1.5</td>
<td>0.5±1.5</td>
<td>0.2±1.5</td>
</tr>
<tr>
<td>Total Background</td>
<td>61.6±16.6</td>
<td>23.4±7.3</td>
<td>5.7±3.3</td>
<td>1.4±1.7</td>
</tr>
<tr>
<td>SM $t\bar{t}$ (8.8 pb)</td>
<td>32.9±5.2</td>
<td>90.2±14.1</td>
<td>113.7±17.6</td>
<td>41.1±6.3</td>
</tr>
<tr>
<td>Total Prediction</td>
<td>94.5±17.4</td>
<td>113.6±15.9</td>
<td>119.4±17.9</td>
<td>42.5±6.5</td>
</tr>
<tr>
<td>Observed</td>
<td>107.0</td>
<td>118.0</td>
<td>115.0</td>
<td>44.0</td>
</tr>
</tbody>
</table>

$X$ is any state with different acceptance than $Wb$

$B(t \rightarrow Zc) < 13\%$

$B(t \rightarrow \text{invisible}) < 9\%$
Flavor-Changing Neutral Currents

- SM FCNC branching fractions are ~$10^{-14}$
  - direct searches for $t \rightarrow Zq$ are sensitive to new physics

\[ \chi^2 = \left( \frac{m_{W,\text{rec}} - m_{W,\text{PDG}}}{\sigma_W} \right)^2 + \left( \frac{m_{t-Wb,\text{rec}} - m_t}{\sigma_{t-Wb}} \right)^2 + \left( \frac{m_{t-Zq,\text{rec}} - m_t}{\sigma_{t-Zq}} \right)^2 \]

Best Fit to Mass $\chi^2$

- $B(t \rightarrow Zq) < 3.7\%$ @ 95% C.L.
Search for $t \rightarrow H^+ b$

- Use $\ell+$jets events with 2 $b$ tags
  - kinematic fit to select $H^+$ daughter candidate jets
  - plot mass of jet pair

![Graph showing data fit with MH120 template][CDF Run II Preliminary]

- $L = 2.2 \pm 0.1 \text{ fb}^{-1}$
- $N(\text{Higgs}) = 44^{+12.34}_{-11.88}$
- $N(\text{W}) = 162.24^{+13.58}_{-13.12}$
- $N(\text{BK}) = 13.78^{+7.16}_{-7.14}$
- $\chi^2 = 0.753920082$

![Graph showing $\text{Br}(t \rightarrow H^+ b)$ with all $H^+$ bands][CDF Run II Preliminary]
Search for $t'$ Quark

- Some SUSY models, and the Little Higgs model, predict the existence of a heavy 4th-generation quark ($t'$)

- search using distributions of reconstructed top mass and sum of jet $p_T$

$m_{t'} > 284$ GeV @ 95% C.L.
Top at the LHC

• LHC will be a top factory ($\sigma \approx 850$ pb):
  - one million events per fb$^{-1}$ ➞ can trade statistics for modes with reduced systematics

• Top will be a valuable standard candle for calibrating jet energy scale and $b$ identification performance

• Expected precisions with 10fb$^{-1}$ of low-luminosity data:
  - Top quark mass: total uncertainty of 1 GeV
  - FCNC: sensitivity down to BF’s of $10^{-3}$ to $10^{-4}$
  - spin correlations: 4% uncertainty on parameters
  - $W$ helicity: measure fractions to 1-2%
Summary

• The precision and variety of top quark measurements is rapidly improving
  - highlighted by mass measurement with precision of 0.8%
  - several measurement of interaction and decay properties, as well as searches for new particles, have not yet revealed any non-SM effects

• The era of single-top production measurements has begun

• The LHC will provide a major improvement in precision

We have learned much about the top quark in the past 13 years
In a few more years it will be as familiar as the Z boson and b quark
The Top Quark in Experiment

- The world’s sample of top quarks comes exclusively from the Tevatron
  - searches for anomalous production also done at HERA
  - “top factory” at LHC is coming soon...
- CDF and DØ detector have similar capabilities for top quark physics
  - data samples are $\sim3\text{fb}^{-1}$ per experiment $\Rightarrow \sim20000\, tt^{-}$ and 7000 single-top events produced
  - branching ratios and selection efficiencies reduce the sample available for analysis
Search for Resonant t\bar{t} Production

CDF Run II Preliminary 1.9 fb⁻¹

Γ_G = 0.30 M_G

- Expected 95% C.L. upper limit ±\sigma
- Expected 95% C.L. lower limit ±\sigma

Unfolded M_{\tilde{t}} [GeV/c²]

- SM Expectation
- SM Uncertainties
- Data, \int L = 1.9 ± 0.1 fb⁻¹

Unfolded M_{\tilde{t}t} [GeV/c²]

- W+Charm
- W+Bottom

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