Top Physics at the Tevatron

Recent Results

Tony Liss

CERN Top Theory Institute  May 22, 2009
Why Study Top?

New Physics?

SM

Production Cross Section
Resonance Production?
Production Kinematics

Top Spin Polarization

W Helicity

Top Charge
Top Spin

Top Mass

M_{TOP}=173 \text{ GeV/c}^2
Is it special?

Decay Modes
Branching ratios

V_{tb}

Rare Decays
\text{t}\rightarrow\text{Zc,}\gamma\text{c,}...

Non-SM Decays
\text{t}\rightarrow\text{H}^+\text{b,}...

\ell^-, \bar{q}', q', \bar{q}, \nu, \ell^+, q, W^+
Outline

- **Top Signature**
  - Separating signal from background
- **$t\bar{t}$ Production Cross Section**
  - Testing QCD, looking for anomalies
- **Measuring the top mass**
  - EWK radiative corrections, $M_W$ & $M_{\text{Higgs}}$
- **$M_{t\bar{t}}$**
  - Searches for anomalous production mechanisms
- **$V_{tb}$ and Single Top Production**
- **Tests of Top Quark Decay**
  - W Helicity
  - Rare decays
- **Forward-Backward Asymmetry**
- **Conclusions**
Identifying Top Events

Events are classified by the decays of the two W bosons. Most analyses use the cleanest channels: Dilepton and Lepton+jets.

When both Ws decay to e or \( \mu \) the event is a “dilepton” event and has two b-jets and missing \( E_T \) from the neutrinos.

When one W decays to e or \( \mu \) the event is a “lepton+jets” event and has four jets and missing \( E_T \) from the neutrino.

Dilepton

Cleanest, but fewest events (BF=4/81)

Lepton+jets

BF=24/81, but significant background from W+jet production.
The key to background suppression in lepton+jets events is identifying at least one b-jet (reduces all of W+jets background to just Wbb).

Two techniques:
1) “Soft muon tagging” identifies a muon in the jet from a semileptonic decay of a B hadron
2) “Secondary vertex tagging” finds the decay vertex of the long-lived B hadron in the jet

Typically we require at least one jet to be “b-tagged” in a top lepton+jets candidate event.
Production Cross Section
\( \sigma = \frac{N - B}{A_{\text{geom}} \cdot \varepsilon \cdot \int Ldt} \)

Candidate events

Backgrounds (from data and Monte Carlo)

Acceptance and efficiencies from Monte Carlo (mostly)

Integrated Luminosity

85% at the Tevatron

15% at the Tevatron
**tt̅ Production Cross Section**

Establishes understanding of signal and background

Provides datasets for other analyses

CDF Run II Preliminary (*)

<table>
<thead>
<tr>
<th>Category</th>
<th>Cross Section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton+Track (L = 1.1 fb⁻¹)</td>
<td>8.3 ± 1.3 ± 0.7 ± 0.5</td>
</tr>
<tr>
<td>Lepton+Track: Vertex tag (L = 1.1 fb⁻¹)</td>
<td>10.1 ± 1.8 ± 1.1 ± 0.6</td>
</tr>
<tr>
<td>Dilepton (L = 2.8 fb⁻¹)</td>
<td>6.7 ± 0.8 ± 0.4 ± 0.4</td>
</tr>
<tr>
<td>Lepton+Jets: Kinematic ANN (L = 2.8 fb⁻¹)</td>
<td>6.8 ± 0.4 ± 0.6 ± 0.4</td>
</tr>
<tr>
<td>Lepton+Jets: Vertex Tag (L = 2.7 fb⁻¹)</td>
<td>7.2 ± 0.4 ± 0.5 ± 0.4</td>
</tr>
<tr>
<td>Lepton+Jets: Soft Electron Tag (L = 2.0 fb⁻¹)</td>
<td>7.8 ± 2.4 ± 1.5 ± 0.5</td>
</tr>
<tr>
<td>Lepton+Jets: Soft Muon Tag (L = 2.0 fb⁻¹)</td>
<td>9.1 ± 1.1 ± 1.0 ± 0.5</td>
</tr>
<tr>
<td>MET+Jets: Vertex Tag (L = 0.3 fb⁻¹)</td>
<td>6.1 ± 1.2 ± 0.8 ± 0.4</td>
</tr>
<tr>
<td>All-hadronic: Vertex Tag (L = 1.0 fb⁻¹)</td>
<td>8.3 ± 1.0 ± 2.0 ± 0.5</td>
</tr>
<tr>
<td>CDF Combined (L = 2.8 fb⁻¹)</td>
<td>7.0 ± 0.3 ± 0.4 ± 0.4</td>
</tr>
</tbody>
</table>

Assume m_t = 175 GeV/c²

85% at the Tevatron

15% at the Tevatron

\[ \sigma(p\bar{p} \rightarrow t\bar{t}) = 7.0 \pm 0.3 \pm 0.6 \text{ pb} \]
$\sigma(\bar{p}p \rightarrow tt) = 8.18^{+0.98}_{-0.87} \text{ pb}$

85% at the Tevatron

15% at the Tevatron
$t\bar{t}$ Production Cross Section

<table>
<thead>
<tr>
<th>Process</th>
<th>3jets</th>
<th>4jets</th>
<th>5jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-tag Data</td>
<td>1988</td>
<td>1030</td>
<td>318</td>
</tr>
<tr>
<td>$Wb\bar{b}$</td>
<td>$42.5 \pm 13.1$</td>
<td>$16.8 \pm 5.8$</td>
<td>$5.4 \pm 2.0$</td>
</tr>
<tr>
<td>$Wc\bar{c}$</td>
<td>$20.7 \pm 6.5$</td>
<td>$9.0 \pm 3.1$</td>
<td>$3.0 \pm 1.1$</td>
</tr>
<tr>
<td>$Wc$</td>
<td>$12.6 \pm 4.0$</td>
<td>$4.1 \pm 1.4$</td>
<td>$1.1 \pm 0.4$</td>
</tr>
<tr>
<td>Mistags</td>
<td>$33.5 \pm 5.5$</td>
<td>$10.2 \pm 3.2$</td>
<td>$2.7 \pm 1.3$</td>
</tr>
<tr>
<td>Non-W</td>
<td>$20.1 \pm 6.8$</td>
<td>$5.6 \pm 4.8$</td>
<td>$2.0 \pm 2.3$</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>$4.3 \pm 0.5$</td>
<td>$1.8 \pm 0.2$</td>
<td>$0.6 \pm 0.1$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$5.1 \pm 0.6$</td>
<td>$2.2 \pm 0.3$</td>
<td>$0.8 \pm 0.1$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$1.5 \pm 0.2$</td>
<td>$0.7 \pm 0.1$</td>
<td>$0.2 \pm 0.0$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$0.3 \pm 0.0$</td>
<td>$0.2 \pm 0.0$</td>
<td>$0.1 \pm 0.0$</td>
</tr>
<tr>
<td>Single Top (s-channel)</td>
<td>$6.4 \pm 0.6$</td>
<td>$2.1 \pm 0.2$</td>
<td>$0.5 \pm 0.1$</td>
</tr>
<tr>
<td>Single Top (t-channel)</td>
<td>$6.1 \pm 0.5$</td>
<td>$2.0 \pm 0.2$</td>
<td>$0.4 \pm 0.0$</td>
</tr>
<tr>
<td>$t\bar{t}$ (7.2pb)</td>
<td>$271.5 \pm 35.8$</td>
<td>$337.1 \pm 44.3$</td>
<td>$120.5 \pm 15.8$</td>
</tr>
<tr>
<td>Total Prediction</td>
<td>$424.6 \pm 44.4$</td>
<td>$391.8 \pm 46.1$</td>
<td>$137.3 \pm 16.5$</td>
</tr>
<tr>
<td>Observed</td>
<td>418</td>
<td>396</td>
<td>138</td>
</tr>
</tbody>
</table>
Limiting Factors

• The dominant background is $Wb\bar{b}$ and predicting it leads to one of the dominant systematics.

<table>
<thead>
<tr>
<th>SYSTEMATIC</th>
<th>$\Delta \sigma$ pb</th>
<th>$\Delta \sigma / \sigma$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>JET ENERGY SCALE</td>
<td>0.16</td>
<td>2.2</td>
</tr>
<tr>
<td>BOTTOM TAGGING</td>
<td>0.38</td>
<td>5.2</td>
</tr>
<tr>
<td>CHARM TAGGING</td>
<td>0.08</td>
<td>1.1</td>
</tr>
<tr>
<td>MIS-TAGS</td>
<td>0.15</td>
<td>2.1</td>
</tr>
<tr>
<td>HEAVY FLAVOR CORRECTION</td>
<td>0.23</td>
<td>3.2</td>
</tr>
<tr>
<td>LUMINOSITY</td>
<td>0.42</td>
<td>5.8</td>
</tr>
<tr>
<td>QCD FRACTION</td>
<td>0.02</td>
<td>0.2</td>
</tr>
<tr>
<td>PARTON SHOWER MODELING</td>
<td>0.13</td>
<td>1.8</td>
</tr>
<tr>
<td>INITIAL/FINAL STATE RADIATION</td>
<td>0.04</td>
<td>0.6</td>
</tr>
<tr>
<td>TRIGGER EFFICIENCY</td>
<td>0.05</td>
<td>0.6</td>
</tr>
<tr>
<td>PDF</td>
<td>0.06</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.67</strong></td>
<td><strong>9.3</strong></td>
</tr>
</tbody>
</table>

This table is for the CDF lepton+jets with vertex tag measurement in 2.7 pb$^{-1}$.
W+Heavy Flavor Backgrounds

W+HF backgrounds come from ALPGEN (+ Pythia) & data.

- Normalize ALPGEN W+jets ("pretag") to data
- Measure "K factor" for ALPGEN HF
  - CDF: vs. data in control region of W+1 jet
  - D0 From MCFM-NLO
- W+HF = Normalized W+jets
  * ALPGEN fraction * K

\[ N_{W+\text{jet}}^{\text{pretag}} = N_{\text{pretag}} \left( 1 - F_{QCD}^{\text{pretag}} \right) - N_{ewk}^{\text{pretag}} - N_{top}^{\text{pretag}} \]

\[ K_{CDF} = 1.4 \pm 0.4 \]
\[ K_{D0} = 1.5 \pm 0.45 \]

NN finds HF composition of W+1 jet data.
CDF & D0 employ 3 techniques for evaluating the QCD fraction.

### Legacy technique: MET vs. ISO

<table>
<thead>
<tr>
<th>Isolation</th>
<th>A</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>B</td>
<td>D</td>
</tr>
<tr>
<td>0.2</td>
<td>E</td>
<td>F</td>
</tr>
</tbody>
</table>

\[
\frac{N_{QCD}^A}{N_{QCD}^B} = \frac{N_{QCD}^C}{N_{QCD}^D}
\]

### Matrix technique

\[
N_{loose} = N_{loose}^{fake-\ell} + N_{loose}^{real-\ell}
\]

\[
N_{tight} = \varepsilon_{fake-\ell} N_{loose}^{fake-\ell} + \varepsilon_{real-\ell} N_{loose}^{real-\ell}
\]

### Anti-electron/jet-electron technique

Fit missing \( E_T \) in data to MC

W+jet template + Anti/jet – electron template from data

The real key is to reduce QCD background AMAP.
\[ p \rightarrow W^- + \ell^+ + q + q' + \bar{q} \]

\[ W^- \rightarrow t + b \]

\[ W^+ \rightarrow \ell^- + \bar{q} \]

\[ \nu + \bar{q} \]

Top Mass
To Measure the Top Mass

**$t\bar{t}$ Production and Decay**

Challenge is to:

a) Properly associate measured objects to initial state quarks and leptons (including neutrino)

b) Extract best possible four-vector for each (energy resolution)
To Measure the Top Mass

**HISTORICALLY....**

- **Step a):** Associate measured with initial-state objects using best match ($\chi^2$) to 3 constraints:
  - $M_{jj} = M_W$
  - $M_{\ell\nu} = M_W$
  - $M_{\ell\nu b} = M_{qqb}$

- **Step b):** Jet energy corrections according to species
  - E scale for light quark jets tuned to match $M_W$
  - E scale for b jets adjusted via tuned MC.

- **After a) & b) it’s just an invariant mass per event.**
  - Final mass comes from best fit to MC template vs. $M_{\text{top}}$
Results

Reconstructed Top Mass

CDF Run II Preliminary (318 pb$^{-1}$)

- 2-tag
- 1-tag($\Gamma$)
- 1-tag(L)
- 0-tag
- Total Signal+Bkgd Fit
- Total Bkgd Fit

Events/(15 GeV/c$^2$)

$m_t^{\text{reco}}$ (GeV/c$^2$)

~3-4 yrs ago...
Controlling the JES Uncertainty

The major advance in Run 2 has been constraining the JES uncertainty using the reconstructed hadronic W
Top Mass – The Modern Era

\[ L = \frac{1}{N(m_t)} \frac{1}{A(m_t, JES)} \sum_{i=1}^{24} w_i \int \frac{f(z_1) f(z_2)}{F F} TF(\vec{y} \cdot JES \mid \vec{x}) |M_{eff}(m_t, \vec{x})|^2 d\Phi(\vec{x}) \]

- Normalization
- Parton assignments
- PDFs
- Matrix element
- Produced→measured
- Transfer function
- Phase space

\( \vec{y} \) are the measured quantities, \( \vec{x} \) the parton-level quantities.

Background is handled with a correction:

\[
\log L_{sig}(m_t, JES) = \sum_{\text{events}} \left[ \log L_i(m_t, JES) - f_{bg}(q_i) \log L_{avg}(m_t, JES \mid bkg) \right]
\]
Alternatively, one can include matrix elements for the background

\[ P_{\text{evt}} (y; m_t, \text{JES}, f_{\text{top}}) = f_{\text{top}} \cdot P_{\text{sig}} (y; m_t, \text{JES}) + (1 - f_{\text{top}}) \cdot P_{\text{bkg}} (y; \text{JES}) \]

Then a likelihood function is built from \( P_{\text{evt}} \):

\[ L (y_1, \ldots, y_n; m_t, \text{JES}, f_{\text{top}}) = \prod_{i=1}^{n} P_{\text{evt}} (y_i; m_t, \text{JES}, f_{\text{top}}) \]
\[ m_t = 172.1 \pm 0.9 \pm 0.7 \text{(JES)} \pm 1.1 \text{GeV/c}^2 = 172.1 \pm 1.6 \text{GeV/c}^2 \]
Top Mass via Matrix Element – D0 Results

For 3.6 pb⁻¹ dataset:

\[ m_t = 173.7 \pm 0.8 \pm 1.6 \text{ GeV/}c^2 = 173.7 \pm 1.8 \text{ GeV/}c^2 \]
Top Mass in the All-Hadronic Channel

Event selection in 6-8 jet events (no MET) via Neural Net:

\[ M_t, \text{ from kinematic fitter:} \]

\[
\chi^2 = \left( \frac{m_{jj}^{(1)} - M_W}{\Gamma_W} \right)^2 + \left( \frac{m_{jj}^{(2)} - M_W}{\Gamma_W} \right)^2 + \left( \frac{m_{jj}^{(1)} - m_t^{rec}}{\Gamma_t} \right)^2 + \left( \frac{m_{jj}^{(2)} - m_t^{rec}}{\Gamma_t} \right)^2 + \sum_{i=1}^{6} \left( \frac{p_{T,i}^{fit} - p_{T,i}^{meas}}{\sigma_i} \right)^2
\]

\[ m_t = 174.8 \pm 1.7 \text{ (stat)} \pm 1.6 \text{ (JES)}^{+1.2}_{-1.0} \text{ (sys)} \text{ GeV}/c^2 \]
# Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>0.73</td>
</tr>
<tr>
<td>Lepton $p_T$ scale</td>
<td>0.11</td>
</tr>
<tr>
<td>Signal modeling (ISR/FSR, PDFs)</td>
<td>0.30</td>
</tr>
<tr>
<td>MC modeling (Pythia vs. Herwig)</td>
<td>0.49</td>
</tr>
<tr>
<td>Multiple interactions (D0)</td>
<td>0.03</td>
</tr>
<tr>
<td>Background modeling</td>
<td>0.26</td>
</tr>
<tr>
<td>Fitting procedure</td>
<td>0.16</td>
</tr>
<tr>
<td>Color reconnection</td>
<td>0.41</td>
</tr>
<tr>
<td>Multiple hadron interactions</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Total Systematic Uncertainty</strong></td>
<td>1.07</td>
</tr>
<tr>
<td><strong>Statistical Uncertainty</strong></td>
<td>0.65</td>
</tr>
</tbody>
</table>
Mass of the Top Quark (*Preliminary)

- CDF-I di-l: 167.4 ± 10.3 ± 4.9
- D0-I di-l: 168.4 ± 12.3 ± 3.6
- CDF-II di-l: 171.2 ± 2.7 ± 2.9
- D0-II di-l: 174.7 ± 2.9 ± 2.4
- CDF-I l+j: 176.1 ± 5.1 ± 5.3
- D0-I l+j: 180.1 ± 3.9 ± 3.6
- CDF-II l+j: 172.1 ± 0.9 ± 1.3
- D0-II l+j: 173.7 ± 0.8 ± 1.6
- CDF-I all-j: 186.0 ± 10.0 ± 5.7
- CDF-II all-j: 174.8 ± 1.7 ± 1.9
- CDF-II trk: 175.3 ± 6.2 ± 3.0
- Tevatron March'09: 173.1 ± 0.6 ± 1.1

$\chi^2/\text{dof} = 6.3/10.0$ (79%)

**m_t** [GeV] vs. **m_W** [GeV]

- LEP2 and Tevatron (prel.)
- LEP1 and SLD

68% CL

**m_H** [GeV]:
- 114
- 300
- 1000

**m_t** [GeV]:
Some New Techniques

\( M_{\text{top}} \) from 2d decay length of B hadron + lepton \( P_T \)

\[
M_t = 175.3 \pm 6.2 \pm 3.0 \text{ GeV/c}^2
\]

\( M_{\ell, \mu} \) from invariant mass of e/\( \mu \) from W boson decay together with “soft muon” from B hadron decay

\[
M_t = 181.3 \pm 12.4 \pm 3.5 \text{ GeV/c}^2
\]
Resonance Production?
Is top produced as we think?

Threshold is $2M + \text{smearing}$

Tail is PDFs + new physics?
The Data

CDF Run 2 preliminary, L=319pb^{-1}

Hint of a resonance?!
The Data

Total Invariant Mass of the $t\bar{t}$ System

CDF Run II Preliminary, $L=955 \text{ pb}^{-1}$

Disappearing with 3x as much data…

Upper Limit on Resonant $t\bar{t}$ Production at CDF

CDF Run II Preliminary $L=955 \text{ pb}^{-1}$
- Expected Limit at 95% C.L.
- Observed Limit at 95% C.L.
- RS KK gluon ($\Gamma' = 0.17M$)
- Topcolor Leptophobic $Z'$
- SM $Z'$ $k = 1.3$
The Data

CDF RunII Preliminary 1.9 fb⁻¹

KS=42.3%

- Data (Nev=371)
- Top
- EW & Single Top
- W+Light Flavor
- Non-W
- W+Charm
- W+Bottom

Events / 20 GeV/c²

\( \bar{t}t \) invariant mass [GeV/c²]
Narrow Resonance Search

D0 reconstructs $M_{tt\bar{t}}$ from leading 3, 4 jets, e/μ and (solved) neutrino.

“Better than kinematic fitter for high mass resonance”
Narrow Resonance Search

D0 reconstructs $M_{tt\bar{t}}$ from leading 3, 4 jets, $e/\mu$ and (solved) neutrino.

“Better than kinematic fitter for high mass resonance”

3 jet events

≥4 jet events
Narrow Resonance Search

D0 reconstructs $M_{tt\bar{t}}$ from leading 3,4 jets, $e/\mu$ and (solved) neutrino.

“Better than kinematic fitter for high mass resonance”

$M_Z<820 \text{ GeV}/c^2 \text{ w}/\Gamma=0.012M$ excluded
Beyond Narrow Resonances

Maltoni HCP 2005:

Non-trivial behavior (peak-dip) due to the interference between the signal and the background.
$d\sigma/dM_{t\bar{t}}$

Measured \hspace{1cm} unfolding \hspace{1cm} Cross section vs. true $M_{t\bar{t}}$

P-value for consistency w/SM = 28%

$\kappa/M_{pl} > 0.16$ excluded at 95% CL
\[ p \rightarrow W^{-} \ell^{+} q \nu \rightarrow W^{+} \ell^{-} \bar{q}' q' \rightarrow p + V_{tb} \]
We have measured:

\[ R \equiv \frac{B(t \rightarrow Wq)}{B(t \rightarrow Wb)} \]

\[ = 0.97^{+0.09}_{-0.08} \quad (D0) \]

\[ = 1.12^{+0.27}_{-0.23} \quad (CDF) \]

From the ratio of \( tt \) events with 0, 1, 2 b-tags

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

An interesting measurement, but not much sensitivity to \( V_{tb} \)

To REALLY measure \( V_{tb} \)...
Single Top Production

“t-channel”
2pb

“s-channel”
0.9pb

Same data selection as $t\bar{t}$ but signal is in $W+2$ jets sample

$$\sigma(q\bar{q}', qg \rightarrow tb) \propto |V_{tb}|^2$$

Difficult due to less distinct signature and very large $W+2$ jets background
S vs. B in Single Top

Here is the expected signal

On top of a substantial background…

A simple counting experiment will not do.

The culprits:

W+HF backgrounds know only to ~30%
Single-Top Analysis Strategy

Full selected data set

- **W + 2 jets**
  - 1 tag
  - ≥ 2 tags
- **W + 3 jets**
  - 1 tag
  - ≥ 2 tags
- **W + 4 jets**
  - 1 tag
  - ≥ 2 tags

**Multivariate methods**

- Neural networks
- Matrix elements
- Likelihood discriminants
- Boosted decision trees

**Combined search**

- t-channel + s-channel = one single-top signal
- Cross section ratio is fixed to SM value.
- Important for "discovery" and test |V_{tb}| << 1

**Separate search**

- Regard t-channel and s-channel as separate processes.
- Important to be sensitive to new physics processes

**Cross section measurement**

- Bayesian treatment

**Hypotheses test**

- Modified Frequentist approach

**Statistical analysis**

- *D0 only*
- *CDF only*

Thanks to Wolfgang Wagner
### Search Methods

**Likelihood**

"Solve" each event kinematically

\[
\chi^2 = \frac{(M_{\ell vb} - 175)^2}{\sigma_{m_i}^2} + \frac{(E_b^{solved} - E_b^{meas})^2}{\sigma_b^2} + \frac{(\Delta E_T)^2}{\sigma_{E_T}^2}
\]

Compute a likelihood for each event based on a set of kinematic variables.

\[
p_{ik} = \frac{\sum_{m=1}^{5} f_{ij,m}}{f_{ij,k}} \quad L_k(\{x_i\}) = \prod_{i=1}^{n_{var}} p_{ik} \frac{\sum_{m=1}^{5} \prod_{i=1}^{n_{var}} p_{ik}}{\sum_{m=1}^{5} \prod_{i=1}^{n_{var}} p_{ik}}
\]

\(k\) runs over S & B samples, \(i\) identifies the kin variable, and \(j\) is the bin in which it falls.

eg. L for **MADEVENT** matrix element

**Matrix Element**

**Parton-level xsec from **MADEVENT** (CDF)**

or **SINGLETOP** (D0) matrix element calc.

\[
P(x) = \frac{1}{\sigma} \int d\sigma(y) dq_1 dq_2 f(x_1) f(x_2) W(y, x)
\]

PDFs Transfer fcns

**Signal**

**Background**

\[
EPD = \frac{b \cdot P_{\text{singletop}}}{b \cdot P_{\text{singletop}} + b \cdot P_{\text{Wbb}} + (1-b) \cdot P_{\text{Wcc}} + (1-b) \cdot P_{\text{Wej}}}
\]

CDF Run II Preliminary
- Events classified based on cumulative set of cuts defining disjoint subsets of events with different signal purities.
- Each cut defines two branches – Pass and Fail
- Terminal nodes (leaves) are reached when no further S/B separation is found
- Each event ends on a leaf with a defined purity.

- Trained on S & B producing one, continuous output discriminant
- Bayesian NN averages over many networks
- Uses highest ranked (best discriminating power) variables.
Kinematic Modeling
Kinematic Modeling

\[ P_T^{\text{lepton}} \]

\[ M_T(W) \]

\[ \eta (\text{jet 1}) \]
Kinematic Modeling

Correlations too!

\[ \kappa_{ij} = \frac{x_i - \bar{x}_i}{\sigma x_i} \cdot \frac{x_j - \bar{x}_j}{\sigma x_j} \]
Single Top Results - CDF

... compared to simulated events normalized to the SM expectation

CDF Run II Preliminary, $L = 3.2$ fb$^{-1}$
- Single Top
- $W+HF$
- $t\bar{t}$
- QCD+Mistag
- Other
- Data
Single Top Results – DØ
TABLE XI: Summary of the relative systematic uncertainties. The ranges shown represent the different samples and channels.

<table>
<thead>
<tr>
<th>Relative Systematic Uncertainties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>6%</td>
</tr>
<tr>
<td>$t\bar{t}$ cross section</td>
<td>18%</td>
</tr>
<tr>
<td>Electron trigger</td>
<td>3%</td>
</tr>
<tr>
<td>Muon trigger</td>
<td>6%</td>
</tr>
<tr>
<td>Primary vertex</td>
<td>3%</td>
</tr>
<tr>
<td>Electron reconstruction &amp; identification</td>
<td>2%</td>
</tr>
<tr>
<td>Electron track match &amp; likelihood</td>
<td>5%</td>
</tr>
<tr>
<td>Muon reconstruction &amp; identification</td>
<td>7%</td>
</tr>
<tr>
<td>Muon track match &amp; isolation</td>
<td>2%</td>
</tr>
<tr>
<td>Jet fragmentation</td>
<td>(5–7)%</td>
</tr>
<tr>
<td>Jet reconstruction and identification</td>
<td>2%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>(1–20)%</td>
</tr>
<tr>
<td>Tag-rate functions</td>
<td>(2–16)%</td>
</tr>
<tr>
<td>Matrix-method normalization</td>
<td>(17–28)%</td>
</tr>
<tr>
<td>Heavy flavor ratio</td>
<td>30%</td>
</tr>
<tr>
<td>$\varepsilon_{\text{real}-e}$</td>
<td>2%</td>
</tr>
<tr>
<td>$\varepsilon_{\text{real}-\mu}$</td>
<td>2%</td>
</tr>
<tr>
<td>$\varepsilon_{\text{fake}-e}$</td>
<td>(3–40)%</td>
</tr>
<tr>
<td>$\varepsilon_{\text{fake}-\mu}$</td>
<td>(2–15)%</td>
</tr>
</tbody>
</table>
CDF Observation!

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Significance Std.Dev. (σ)</th>
<th>Sensitivity Std.Dev. (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN</td>
<td>3.5</td>
<td>5.2</td>
</tr>
<tr>
<td>ME</td>
<td>4.3</td>
<td>4.9</td>
</tr>
<tr>
<td>LF</td>
<td>2.4</td>
<td>4.0</td>
</tr>
<tr>
<td>LFS</td>
<td>2.0</td>
<td>1.1</td>
</tr>
<tr>
<td>BDT</td>
<td>3.5</td>
<td>5.2</td>
</tr>
<tr>
<td>SD</td>
<td>4.8</td>
<td>&gt;5.9</td>
</tr>
<tr>
<td>MJ</td>
<td>2.1</td>
<td>1.4</td>
</tr>
<tr>
<td>Combined</td>
<td>5.0</td>
<td>&gt;5.9</td>
</tr>
</tbody>
</table>

**CDF Preliminary Single Top Summary**

For $M_{top} = 175$ GeV/c$^2$

- **S-Channel Likelihood Function**
  
  $1.5 \pm 0.9$

- **Neural Network**
  
  $3.2$ fb$^{-1}$

  $1.8 \pm 0.6$

- **Matrix Element**
  
  $3.2$ fb$^{-1}$

  $2.5 \pm 0.7$

- **Likelihood Function**
  
  $3.2$ fb$^{-1}$

  $1.6 \pm 0.8$

- **Boosted Decision Tree**
  
  $3.2$ fb$^{-1}$

  $2.1 \pm 0.7$

- **Combination (Lepton+Jets)**
  
  $3.2$ fb$^{-1}$

  $2.1 \pm 0.6$

- **MET+Jets**
  
  $2.1$ fb$^{-1}$

  $4.9 \pm 2.6$

- **Combination (All Channels)**
  
  $3.2$ fb$^{-1}$

  $2.3 \pm 0.6$
**D0 Observation!**

<table>
<thead>
<tr>
<th>Method</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision Trees</td>
<td>3.74</td>
</tr>
<tr>
<td>Bayesian NNs</td>
<td>4.70</td>
</tr>
<tr>
<td>Matrix Elements</td>
<td>4.30</td>
</tr>
<tr>
<td>BLUE Combination</td>
<td>4.16</td>
</tr>
<tr>
<td>BNN Combination</td>
<td>3.94</td>
</tr>
</tbody>
</table>

**March 2009**

- **σ (p̅p → tb+X, tqb+X) [pb]**
  - N. Kidonakis, PRD 74, 114012 (2006) $m_{top} = 170$ GeV

**DØ Combination**

- 67.8M pseudo-datasets (background-only)
- 17 above measured cross section
- $p$-value $= 2.5 \times 10^{-7}$
- Observed significance $= 5.03 \sigma$

- $\sigma_{meas} = 3.94$ pb
\[ V_{tb} \]

\[ |V_{tb, meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb, SM}|^2 \]

|CDF|

\[ |V_{tb}| = 0.91 \pm 0.11 \text{ (stat+syst)} \pm 0.07 \text{ (theory)} \]

|V_{tb}| > 0.71 at 95% C.L.

|D0:|

\[ |V_{tb f_1}| = 1.07 \pm 0.12 \]

0.78 < |V_{tb}| < 1 \text{ @ 95% CL}
\[ W^- \rightarrow \ell^- + q + A + q' - \nu \]

W Helicity

Diagram showing the decay of a W particle into a lepton (\( \ell^- \)), a quark (\( q \)), an anti-quark (\( \overline{q} \)), and a neutrino (\( \nu \)).
Does the Top Quark Decay as Expected?

Standard Model at the tWb vertex gives

\[ F_0 = \left( 1 + 2 \left( \frac{M_W}{M_t} \right)^2 \right)^{-1} = 70\% \text{ Longitudinal Ws} \]

Measure via angular distribution:

- left-handed: \( \frac{1}{4} \left( 1 - \cos \theta^* \right)^2 \)
- longitudinal: \( \frac{1}{2} \left( 1 - \cos^2 \theta^* \right) \)
- right-handed

Or: Matrix element technique

\[ L(f_0, C_s) = \prod_{i=1}^{N} \left[ C_s P_{\bar{t}t} \left( \bar{x}_i; f_0 \right) + (1 - C_s) P_{W+jets} \left( \bar{x}_i \right) \right] \]

\[ P(\bar{x}) = \frac{1}{\sigma_{obs}} \int \frac{d\sigma(\bar{y})}{d\bar{y}} f(q_1) f(q_2) W(\bar{x}, \bar{y}) dq_1 dq_2 dp_{\pi} dp_{\bar{\pi}} d\bar{y} \]

V-A → no right handed W bosons
W Helicity - Matrix Element

\[ L(f_0, C_s) = \prod_{i=1}^{N} \left[ C_s P_{t\bar{t}}(\tilde{x}_i; f_0) + (1 - C_s) P_{W+jets}(\tilde{x}_i) \right] \]

\[ C_s = \text{signal fraction} \]

\[ P(\tilde{x}) = \frac{1}{\sigma_{obs}} \int \frac{d\sigma(y)}{dy} f(q_1) f(q_2) W(\tilde{x}, \tilde{y}) dq_1 dq_2 dp_{t\bar{t}}^y dp_{t\bar{t}}^x d\tilde{y} \]

Differential xsec including helicity

\[ f_0 = 0.64 \pm 0.08(\text{stat}) \pm 0.07(\text{sys}) \]

\[ f_+ \equiv 0 \]

Systematics here are dominated by MC modeling (\(f_0\) measured \(\rightarrow f_0\) corrected)
Two reconstruction techniques used

$\cos \theta^*$

Dominant systematics are background normalization & shape, and JES.
W Helicity – \( \cos \theta^* \)

D0’s latest uses lep+jets & dilep, & hadronic W decays

A kinematic discriminant provides extra S-B separation

\[ f_0 = 0.490 \pm 0.106 \text{(stat)} \pm 0.085 \text{(sys)} \]
\[ f_+ = 0.110 \pm 0.059 \text{(stat)} \pm 0.052 \text{(sys)} \]
D0 combines the single-top result and W helicity measurements to set limits on anomalous couplings.

\[
L = -\frac{g}{\sqrt{2}} \overline{b} \gamma^\mu V_{tb} \left( f_1^L P_- + f_1^R P_+ \right) t W^- - \frac{g}{\sqrt{2}} \overline{b} \frac{-i \sigma^{\mu\nu} q_v V_{tb}}{M_W} \left( f_2^L P_- + f_2^R P_+ \right) t W^- + h.c.
\]

\[P_\pm = (1 \pm \gamma_5)/2\]

\[\equiv 0\] in S.M.

Non-zero values would change W helicities and kinematics and rate of single-top production.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Coupling $f_1^L$, $f_1^R$</th>
<th>Coupling limit if $f_1^T = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(f_1^L, f_1^R)$</td>
<td>$</td>
<td>f_1^L</td>
</tr>
<tr>
<td>$(f_1^L, f_2^L)$</td>
<td>$</td>
<td>f_1^L</td>
</tr>
<tr>
<td>$(f_1^L, f_2^R)$</td>
<td>$</td>
<td>f_1^L</td>
</tr>
</tbody>
</table>
Rare Decays
$t \rightarrow Zc, \gamma c, \ldots$
**FCNC Search**

$t \rightarrow Zq$

BR $\sim 10^{-14}$ in SM $\Rightarrow$ Any observation is PBSM!

Search in $Z \rightarrow ee, \mu \mu + 4$ or more jets
Dominant backgrounds are Z+4 jets, WW, WZ.
Background suppression is achieved via a mass $\chi^2$ variable:

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

Note: final state is neutrino-free.

$B(t \rightarrow Zq) < 3.7\%$ @ 95% C.L.
FCNC in Single Top Production

Anomalous production

..but SM decay

No signal observed ⇒ \( \sigma_{\text{FCNC}} < 1.8\text{pb} \)

\[
\kappa_{tu}/\Lambda < 0.018 \text{ TeV}^{-1} \quad (\kappa_{tcg} \equiv 0)
\]

\[
\kappa_{tcg}/\Lambda < 0.069 \text{ TeV}^{-1} \quad (\kappa_{tug} \equiv 0)
\]

\[
B(t \rightarrow u + g) < 3.9 \times 10^{-4}
\]

\[
B(t \rightarrow c + g) < 5.7 \times 10^{-3}
\]

Very hard to distinguish SM from FCNC!
Production Kinematics
Forward-Backward Asymmetry

\[
A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}
\]

Use the hadronic side to measure top rapidity.

Tag t vs t\bar{t} with lepton charge.

\[
\chi^2 = \sum_{\text{leptons, jets}} \frac{(p_i^{t,\text{meas}} - p_i^{t,\text{fit}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,\text{meas}} - p_j^{UE,\text{fit}})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{bt\nu} - M_t)^2}{\Gamma_t^2}
\]
$A_{fb}$

Reconstructed Top Rapidity

CDF II Preliminary

$L = 3.2 \text{ fb}^{-1}$

$A_{fb}^{Data} = 0.098 \pm 0.036$

$A_{fb}^{Signal} = 0.02 \pm 0.0071$

$A_{fb}^{Sig+Bkg} = 0.0028 \pm 0.0059$

$A_{fb}^{Bkg} = -0.059 \pm 0.0079$

$A_{fb}^{corrected} = 0.193 \pm 0.065 \pm 0.024$
Conclusions

• A broad program of measurements of the properties of the top quark is underway at the Tevatron.
• Single top has (finally) been observed!
• The Run 2 dataset (CDF+D0) is beginning to provide sensitive searches for PBSM in top production and decay.
• The uncertainty on the top mass, *individually*, from CDF and D0 is <1% (!!!)
  – The Higgs appears to be light…
• These measurements will focus the work to be done at the top factory called the LHC.