Top-Quark Physics at the Tevatron

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The discovery of the Top Quark

• Top is massive: $m_t = 176 \pm 13$ GeV (using 12 Top events!)
• Short lifetime $\tau \approx 5 \cdot 10^{-25}$s $\Rightarrow$ decay before hadronisation
• Very little is known about this particle…
• Is this really the Standard-Model Top Quark???
Where can we study Top Quarks?

here!
The Tevatron @ Fermilab

- **Tevatron** (ring radius = 1 km)
  - pp collisions at $\sqrt{s} = 1.96$ TeV
  - 36 bunches (396 ns spacing)
  - Currently the high energy frontier!
  - World record lumi: $2.85 \cdot 10^{32}$/cm$^2$s

Diagram of Fermilab facilities:
- Booster
- Main Injector
- CDF
- DZero
- Chicago
Top Quark Production

@ Tevatron: The precision era

Top Discovery: Tevatron “Run I” (’92-’96): ~125pb⁻¹, \( \sqrt{s} = 1.8 \) TeV.

Now “RunII”: ➢ Increased luminosity
➢ Increased \( \sqrt{s} : 1.96 \) TeV \( \Rightarrow +30\% \sigma_{\text{Top}} \)


record 40% Run I / week

Top Events: 15 times Run I…

\[ 10^{-10} \]
Top Quark Production & Decay

- **Main production** of Top Quarks – via strong interaction in *pairs*:

  \[ \frac{85\%}{\text{SM}} \quad + \quad \frac{15\%}{\text{EW}} \]

  \[ \text{Theoretical expectation: } \sigma_{\bar{t}t} = (6.77 \pm 0.65) \text{ pb} \]
  
  N. Kidonakis, priv. comm., \( m_t = 175 \text{ GeV/c}^2 \)

- **EW Single Top** production: first evidence by DØ, *see next presentation*!

- **SM Top decay** \( \approx 100\% \text{ Wb} \) ⇒ Final states determined by W decay mode

  ⇒ 2 b-jets,
  ⇒ Up to two charged leptons/neutrinos
  ⇒ Up to four additional jets

  Need to reconstruct/identify:
  - Electrons, muons, taus,
  - Missing transverse energy
  - Jets/b-jets
Classification of Top Quark pair events

Dilepton: 10%
Two high-$p_T$ jets
Two high-$p_T$ leptons

Lepton + Jets: 44%
Four high-$p_T$ jets
One high-$p_T$ lepton

All Hadronic: 46%
Six high-$p_T$ jets

- low branching fraction
- low background
  (WW+jets, Z+jets, W+jets)

- high branching fraction
  • high background
    (W+jets, “QCD” multijet production)
The Tevatron Collider Experiments

Multi-purpose collider detectors:

- 13 countries
- 58 institutions
- ~620 physicists

- 18 countries,
- 89 institutions,
- ~610 physicists

Top Quark physics needs everything:

- Central tracking and vertexing (momentum measurement, b-jet ID)
- Excellent calorimetry (jets, electrons, missing transverse energy)
- Good muon detection in large acceptance
What do we want to measure?

**Top Pair Production:**
- Non-SM Decays: \( t \rightarrow H^+ b \)
- Rare Decays: \( t \rightarrow Z/\gamma c \)
- CKM Matrix: \( |V_{tb}| \)
- Branching Ratios
- Decay Modes
- Spin
- Mass
- Charge
- Lifetime

**Single Top Production:**
- Production Cross Section
- Resonant Production?
- Production Kinematics
- Production Mechanism
- Spin Correlations
- CKM Matrix: \( |V_{tb}| \)
- Spin Polarisation
- Production Cross Section

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...everything!

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Selected Measurements for today

- **Production rate:**
  Test Standard Model (QCD) predictions

- **Charge:**
  Is the charge of the Top $Q = 2/3$?

- **W-helicity:**
  Test V-A interaction

- **Mass:**
  Radiative corrections on the W mass allow constraints on **Higgs mass** from $m_W, m_t$

Is this the Standard Model Top Quark?
Top Quark Pair Production: Dilepton channels

- **Signature:** isolated high $p_T$ ee, $\mu\mu$, $e\mu$, $\geq 2$ jets, $E_T$

- **Main Backgrounds:**
  - $WW(\rightarrow ee, \mu\mu, e\mu) + \text{jets}$
  - $Z/\gamma^* (\rightarrow \tau\tau \rightarrow e\mu) + \text{jets}$
  - $Z/\gamma^* (\rightarrow ee, \mu\mu) + \text{jets}$
  - $W+\text{jets}$ (jet fakes isolated $e, \mu$)

<table>
<thead>
<tr>
<th>Source</th>
<th>ee</th>
<th>$\mu\mu$</th>
<th>$e\mu$</th>
<th>$\ell\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total background</td>
<td>6.86±1.70</td>
<td>10.47±2.06</td>
<td>8.23±2.30</td>
<td>25.56±5.54</td>
</tr>
<tr>
<td>$t\bar{t}$ ($\sigma = 6.7 \text{ pb}$)</td>
<td>12.18±0.94</td>
<td>13.60±1.04</td>
<td>30.17±2.30</td>
<td>55.95±4.26</td>
</tr>
<tr>
<td>Total SM expectation</td>
<td>19.04±2.26</td>
<td>24.08±2.68</td>
<td>38.40±3.90</td>
<td>81.52±8.92</td>
</tr>
<tr>
<td><strong>DATA</strong></td>
<td>16</td>
<td>26</td>
<td>35</td>
<td>77</td>
</tr>
</tbody>
</table>

$\sigma_{tt} = 6.2 \pm 1.1 \text{ (stat.)} \pm 0.7 \text{ (syst.)} \pm 0.4 \text{ (lumi) pb}$

(Standard Model expectation: 6.7 pb)
Top Quark Pair Production: Lepton+Jets channels

**Signature:** isolated high $p_T$ lepton, $E_T$, ≥4 jets

**Main Backgrounds:**
- Multijet production with fake lepton, $E_T$
- $W$ production, $W \rightarrow \ell + \nu_\ell$, ≥4 jets from gluon radiation
- Before b-jet identification: high background levels
- Use multivariate discriminant (event topology/kinematics based) to extract signal

$\mu^+ \nu$

$0.4 \pm (0.7 \pm 3.6) \pm 9.0 \pm 8.0 \sigma_{tt}$

**No b-jet identification required:**
- less model-dependent measurement
- test understanding of sample composition
- not full information used ⇒ reduced precision

$\sigma_{tt} = 6.3^{+0.9}_{-0.8} \text{ (stat)} \pm 0.7 \text{ (syst)} \pm 0.4 \text{ (lumi) pb}$

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$\bar{t}t \rightarrow \mu+\text{jets candidate event}$

$\mu$

mip signal in calorimeter

Jet 1

Jet 5

Jet 3

Jet 4

$\tau_B \approx 1.5 \text{ ps} \Rightarrow \beta \gamma \epsilon \tau > \text{mm}$
Lifetime b-tagging

- Separate $b$-jets from light-quark and gluon jets ⇒ reject most multijet & $W+$jets background processes
- $\tau_B \approx 1.5 \text{ ps} \Rightarrow \beta \gamma c \tau > \text{mm}$
- Use impact parameter / reconstructed secondary vertex information
- “Tagging” efficiencies:
  - $b$-jet $\approx 50\%$
  - $c$-jet $\approx 10\%$
  - light-jet $\approx 0.5\%$

(dca = distance of closest approach)
Top Quark Pair Production: Lepton + Jets channels

Strategy:

- **Require b-tagged jets** in the event to further suppress background
- Analyse eight channels separately: e/µ, 1/≥2 tags, 3/≥4 jets
- Perform maximum likelihood fit to observed number of events in the different channels

\[
\ell + \text{jets} : \sigma_{p\bar{p}\to t\bar{t}+X} = 8.3^{+0.6}_{-0.5}\text{(stat)}^{+0.9}_{-1.0}\text{(syst)} \pm 0.5\text{(lumi)} \text{ pb}
\]
Top Quark Pair Production: All hadronic channel

- **Signature**: \( \geq 6 \) jets, no isolated high \( p_T \) lepton, no \( E_T \).

- **Main Backgrounds**:
  - Overwhelming “QCD” Multijet production
  - Jets from multiple interactions
  - Require \( \geq 1 \) b-jets, use multivariate kinematical selection (based on total transverse energy, masses of jet combinations,…)

\[ \sigma_{tt} = 8.3 \pm 1.0 \text{ (stat)}^{+2.0}_{-1.5} \text{ (syst)} \pm 0.5 \text{ (lumi)} \text{ pb} \]
Top Quark Pair Production: cross sections

DØ Run II  * = preliminary

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>dilepton/l+jets (topological)</td>
<td>7.1 ± 1.2, 1.4, -1.2, -1.1</td>
</tr>
<tr>
<td>dilepton* (topological)</td>
<td>6.8 ± 1.2, 0.9, -1.1, -0.8</td>
</tr>
<tr>
<td>l+track/emu* (combined)</td>
<td>8.6 ± 1.9, 1.1, -1.7, -1.1</td>
</tr>
<tr>
<td>tau+jets* (b-tagged)</td>
<td>5.1 ± 4.3, 0.7, -3.5, -0.7</td>
</tr>
<tr>
<td>alljets (b-tagged)</td>
<td>4.5 ± 2.0, 1.4, -1.9, -1.1</td>
</tr>
<tr>
<td>l+jets (b-tagged)</td>
<td>6.6 ± 0.9, -0.9</td>
</tr>
<tr>
<td>l+jets* (μ-tagged)</td>
<td>7.3 ± 1.2, 0.0, -1.8</td>
</tr>
<tr>
<td>l+jets* (NN b-tagged)</td>
<td>8.3 ± 0.3, 0.9, -0.7, 0.7</td>
</tr>
<tr>
<td>l+jets* (topological)</td>
<td>6.3 ± 0.9, 0.7, -0.8, 0.7</td>
</tr>
</tbody>
</table>

m_{t\bar{t}} = 175 GeV

Cacciari et al., JHEP 0404:068 (2004)

Lepton+Track
(L=1070 pb⁻¹)

8.3 ± 1.3 ± 0.7 ± 0.5

Dilepton
(L=1200 pb⁻¹)

6.2 ± 1.1 ± 0.7 ± 0.4

Lepton+Jets: Kinematic ANN
(L= 760 pb⁻¹)

6.0 ± 0.6 ± 0.9 ± 0.3

Lepton+Jets: Vertex Tag
(L=1120 pb⁻¹)

8.2 ± 0.5 ± 0.8 ± 0.5

Lepton+Jets: Soft Muon Tag
(L= 760 pb⁻¹)

7.8 ± 1.7 ± 1.0 ± 0.5

MET+Jets: Vertex Tag
(L= 311 pb⁻¹)

6.1 ± 1.2 ± 1.4 ± 0.4

All-hadronic: Vertex Tag
(L=1020 pb⁻¹)

8.3 ± 1.0 ± 2.0 ± 0.5

Combined (old SLT, all-had)
(L= 760 pb⁻¹)

7.3 ± 0.5 ± 0.6 ± 0.4
Measurement of the Top Charge

- Standard Model Top Quark has charge $Q = +\frac{2}{3}$
- Pairing the $W$ boson to the $b$ quark jet in Top pair events is ambiguous
- Discovered particle could have charge $|Q| = \frac{2}{3}$ or $|Q| = \frac{4}{3}$
- Use pure top samples to investigate: double-tagged $l$+jets, tagged dilepton
- Exotic model*:
  - Predicts quark doublet with charges $Q = -\frac{1}{3}$ and $Q = -\frac{4}{3}$
  - Particle discovered at Fermilab would be $Q = -\frac{4}{3}$ particle
  - The Standard Model Top Quark would have $m \approx 270$ GeV.

* D. Chang et. al., PRD 59, 091503 (1999)
Measurement of the Top Charge

- **Pairing of W and b-jet:**
  - Lepton+jets: kinematic fit
  - Dilepton: select on $M^2(l,b)$

- **W-charge:** from lepton charge

- **b-jet charge:** use momentum-weighted sum of charged tracks associated to b-jet

- **Calibration:** $b\bar{b}$ data using semi-leptonic b-jet decays to determine the charge (corrected for c-jets and B mixing)

- 2 measurements per event

Bayes factor (odds of SM vs. exotic model):
- DZero: 4.3 (L+jets, 370 pb$^{-1}$)
- CDF: 8.5 (Dilepton, L+jets, 695 pb$^{-1}$)

DZero&CDF data strongly favour SM!
W Helicity

Standard Model top decay: V-A interaction (like for all fermions)

**W helicity states:**

- **left-handed fraction:** $f_-$
- **longitudinal fraction:** $f_0$
- **right-handed fraction:** $f_+$

**In Standard Model:**

- $\sim 30\%$
- $\sim 70\%$
- $\sim 0.036\%$

$\Rightarrow$ Measure angular distribution of charged lepton wrt. top in W rest frame: $\cos\theta^*$

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Use Lepton+Jets dataset
≥4 jets, ≥1b-jet identified:
subtract background, correct for detector acceptance

Fit $f_0$, fixed $f_+ = 0$ (SM value):
$f_0 = 0.59 \pm 0.12\text{(stat)}^{+0.07}_{-0.06}\text{(syst)}$

Fit $f_+$, fixed $f_0 = 0.7$ (SM value):
$f_+ \leq 0.10 @ 95\% \text{ C.L.}$
Top Quark Mass Measurements

Many Methods exist - general features:
• Measure observable sensitive to Top mass
• Map partons to reconstructed objects (combinatorics!)
• Calibrate with pseudo-experiments
• Obtain mass via maximum likelihood

Need to relate the reconstructed calorimeter jets back to parton level:
Jet Energy Scale is crucial!

Top events: W boson decay products allow for additional in-situ jet energy calibration
Top Quark Mass Measurements: Matrix Element Method

- Matrix Element Method: yields so far most precise measurements
- Use four-vectors of reconstructed objects to calculate per event probability density for being signal/background as function of $m_t$
- Maximises use of information on the event, but CPU intense calculations
- Product of event probabilities allows to extract the most likely mass value:

$$P_{\tilde{t}\tilde{t}}(x, m_t, JES) = \frac{Acc(x)}{\sigma_{\tilde{t}\tilde{t}}(m_t)} \int dq_1 dq_2 f(q_1) f(q_2) d\sigma(y, m_t) T(x, y, JES)$$

- Normalisation
- Partonic differential Cross Section, based on LO Matrix Element
- Acceptance
- Initial state
- Transfer Function: Prob. to measure $x$ from parton-level $y$

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Top Quark Mass Measurements: Matrix Element Method

- \( P_{\text{sig}} = \text{sum over all 24 possible object-parton assignments in } l+\text{jets events, weighted with b-tagging event probabilities} \)
- Event probability \( P = f_{\text{sig}} P_{\text{sig}}(x, m_t, \text{JES}) + (1-f_{\text{sig}}) P_{\text{bg}}(x) \)
- Calibrate method against simulation

\[
m_{\text{Top}} = 170.5 \pm 2.4(\text{stat.} + \text{JES}) \pm 1.2(\text{syst.}) \text{ GeV}
\]

**dominant systematic errors:**
- relative light/b JES: \( \pm 0.57 \) GeV
- b fragmentation: \( \pm 0.54 \) GeV
- signal fraction: \( +0.53 -0.24 \) GeV
- signal modelling: \( \pm 0.45 \) GeV
Tevatron Top Quark Mass

weights in world average:

\[ \Delta m_t = 1 - 1.5 \text{ GeV} \] in Run II

1.1 \% precision!
Top Quark Mass and SM Higgs

\[ \Delta m_W \propto m_t^2 \]

\[ \Delta m_W \propto \ln m_H^2 \]

- Radiative corrections on the W mass allow constraints on Higgs mass from \( m_W, m_t \)

Preferred \( m_H \): 76^{+33}_{-24} \text{ GeV} \quad 114 \text{ GeV} < m_H < 182 \text{ GeV} @ 95\% \text{ C.L.}
Summary

- Important Top Quark properties have been measured:
  - Top pair production cross section: precision $\rightarrow 10\%$
  - Top charge: consistent with Standard Model
  - W helicity determined: consistent with Standard Model
  - Top mass: $170.9 \text{ GeV} \pm 1.1\%$ – Most precise quark mass!
- Mass and cross section measurements become systematics limited
- Other properties can be measured for the first time w/ large datasets
- There’s still plenty room for surprises…

More measurements / information available online:

- [http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html](http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html)
Outlook

Integrated Luminosity [fb⁻¹]

Design Projection: 8.5 fb⁻¹
Base Projection: 4.4 fb⁻¹

(Start of Fiscal Year)

More exciting results ahead!

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