Top Quark Production at the Tevatron

Christian Schwanenberger

University of Manchester

on behalf of the CDF and DØ Collaborations

Hadron Collider Physics Symposium

Toronto

08/25/2010
The Top Quark

- needed as isospin partner of bottom quark

- discovered in 1995 by CDF and DØ: $m_{\text{top}} \sim$ gold atom

- large coupling to Higgs boson $\sim 1$: important role in electroweak symmetry breaking?

- short lifetime: $\tau \sim 5 \cdot 10^{-25} \text{s} \ll \Lambda_{\text{QCD}}^{-1}$: decays before fragmenting → observe “naked” quark
Top History

1995, CDF and DØ experiments, Fermilab

**discovery**

- PRL 74, 2632 (1995)
- PRL 74, 2626 (1995)

**17 events**

- DØ

**19 events**

- CDF
Top History

1995, CDF and DØ experiments, Fermilab

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

17 events

DØ

~1000 events

19 events

CDF

today

l+4 jets

≥ 1 b-tag

Reconstructed Mass (GeV/c²)

Events/(10 GeV/c²)

Mt_{reco}

CDF Run II Preliminary (4.8 fb^{-1})

Data

bkgd+ttop25 M_{t} = 172.5 GeV/c²

bkgd

Events/(20 GeV/c²)

Fitted Mass (GeV/c²)

Mass (GeV/c²)

Entries/(10 GeV/c²)
Top History

**discovery**

1995, CDF and DØ experiments, Fermilab

17 events

DØ

19 events

CDF

**precision**

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

**today**

~1000 events

**Tevatron**

19 events

PRL 74, 2626 (1995)

17 events

PRL 74, 2632 (1995)

l+4 jets

≥ 1 b-tag

Top Quark Mass Uncertainty

- H+jets DØ measurement
- Combined DØ measurement
- Tevatron combination
- Projected future uncertainty range

Total Top Quark Mass Uncertainty (GeV/c^2)

Fitted Mass (GeV/c^2)

Events/(200 GeV/c^2)

100 200

Reconstructed Mass (GeV/c^2)

Events/(100 GeV/c^2)

80 120 160 200 240 280

 faded
Top History

1995, CDF and DØ experiments, Fermilab

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

17 events
DØ

~1000 events

19 events
CDF

l+4 jets ≥ 1 b-tag

Top Quark Mass Uncertainty

Tevatron

precision

searches

today

19 events
CDF

17 events
DØ

Top Quark Production – Christian Schwanenberger – HCP 2010, Toronto
Top History

### discovery

- **17 events**
  - DØ
  - **Fitted Mass (GeV/c²)**
  - **Events/(20 GeV/c²)**

### precision

- **19 events**
  - CDF
  - **Reconstructed Mass (GeV/c²)**
  - **Events/(10 GeV/c²)**

### today

- **~1000 events**
  - **Mt_{reco}**
  - **l+4 jets**
  - **≥ 1 b-tag**

### 1995, CDF and DØ experiments, Fermilab

### LHC: top factory

- **Top Quark Mass Uncertainty**
  - H+jets DØ measurement
  - Combined DØ measurement
  - Tevatron combination
  - Projected future uncertainty range

- **Run 1**
  - Δ M/M<1%
  - Δ M < 1 GeV/c²
  - 16 fb⁻¹

- **Top Quark Mass Uncertainty**
  - **Total Top Quark Mass Uncertainty (GeV/c²)**
  - **Integrated Luminosity (fb⁻¹)**
Top Quark Analyses at the Tevatron

up to 5.7 fb$^{-1}$ of data: several 1000 top candidates per experiment

top pair production

anomalous couplings
rare decays
branching ratios
CKM-Matrix-Element $|V_{tb}|$
new particles

mass, charge,
width, lifetime

W helicity

production cross-section,
production kinematics
production through resonances
new particles

spin correlations
charge asymmetry $A_{FB}$

single top production

production cross section, CKM-Matrix-Element $|V_{tb}|$,
anomalous couplings, searches for new particles
up to 5.7 fb\(^{-1}\) of data: several 1000 top candidates per experiment

**top pair production**

- production cross-section
- production through resonances
- new particles

- CKM-Matrix-Element |V\(_{tb}\)|
- anomalous couplings
- rare decays
- branching ratios

**single top production**

- production cross section
- CKM-Matrix-Element |V\(_{tb}\)|
- anomalous couplings
- searches for new particles

spin correlations
charge asymmetry \(A_{FB}\)
mass, charge, width, lifetime
W helicity
Outline

- strong production
- top pair production cross section
- searches for new physics
- electroweak production
- single top production cross section
- searches for new physics
- conclusions
Outline

**strong production**
- top pair production cross section
- searches for new physics

**electroweak production**
- single top production cross section
- searches for new physics

**conclusions**
Top Quark Pair Production

\[ \sigma_{tt} = 7.46^{+0.48}_{-1.07} \text{ pb in NNLO} \]

\( m_{\text{top}} = 172.5 \text{ GeV} \)
Top Pair Signatures

top decay:

\[
\begin{align*}
&\text{~100\%} \\
&\begin{array}{c}
\text{v, q} \\
\text{l^+, q'} \\
\text{b} \\
\text{t}
\end{array}
\end{align*}
\]

\[
\begin{align*}
&\text{W^+} \\
&\text{W^-} \\
&\text{cs} \\
&\text{ud} \\
&\text{e^+} \\
&\text{e^-} \\
&\text{\mu^+} \\
&\text{\mu^-} \\
&\text{\tau^+} \\
&\text{\tau^-} \\
&\text{\tau\tau} \\
&\text{\tau e/\tau\mu} \\
&\text{\mu e/\mu\mu} \\
&\text{dilepton (e/\mu)} \\
&\text{lepton + jets} \\
&\text{tau + jets} \\
&\text{all jet} 46\% \\
&\text{all hadronic} \\
&\text{\tau's 14\%} \\
&\text{~100\%} \\
&\text{e/\mu + jet 34\%}
\end{align*}
\]
Lepton+jets Signatures

**signal**

- $q\bar{q}$
- $t\bar{t}$
- $W^+W^-$
- $\nu\bar{\nu}$
- $q'\bar{q}'$
- $e/\mu + \text{jet}$

**3000 times higher rate**

**background**

- $W + \text{jets}$
- $gqg$
- $q'\bar{q}'$
- $10^{10}$ times higher rate

**multijets**

**Jet 1**

- $\mu^-$
- SV
- IP

**Jet 2**

- SV
- IP
Dilepton Signatures

**signal**

\[ q \rightarrow t \rightarrow W^+ b, \ \bar{q} \rightarrow \bar{t} \rightarrow W^- \bar{b} \]

**background**

\[ Z + \text{jets} \]

300 times higher rate

- less statistics
- less background

**ee, e\mu, \mu\mu**

→ electron+muon event with b-tagging
Lepton+Jets Topological Cross Section

measure if production rate is as predicted by NLO QCD

- kinematic properties allow separation between signal and background

use variables such as:

- energy-dependent quantities:
  - e.g. Transverse mass of leptonic top

- angular dependent:
  - e.g. sphericity

Boosted Decision Trees
**Lepton+Jets Topological Cross Section**

- **Data**: $\sigma_{tt} = 7.70^{+0.70}_{-0.79}$ (stat+syst+lumi) pb
- **Top Quark**: $m_{\text{top}} = 172.5$ GeV
- **W+jets**
- **Multijets**

---

**Graph Details**

- DØ Preliminary, $L=4.3$ fb$^{-1}$
- Histogram with categories: data, top pair, other, W+jets, multijets
- Discriminant Output scale from 0 to 1
- Event counts from 0 to 450

---

**Notes**

- Event classification and cross-section analysis for top quark and W+jets production.
**b-tagging**

- **B hadron lifetime** $\tau \sim 1\,\text{ps}$
- **B hadrons travel** $L_{xy} \sim 3\,\text{mm before decay}$

- Secondary vertex tagger
- 45% b-jet tagging efficiency (with fake rate of 1%)

- Form a 7-variable neural network
- b-jet tagging efficiency 59% (with fake rate of 1%)

---

Lepton+Jets Cross Section with b-tagging

Very powerful tool to reduce the background

- limited by systematics
- luminosity dominates at ~6%
- b-tagging second largest

$$\sigma_{tt} = 7.93^{+1.04}_{-0.91} \text{ (stat+syst+lumi) pb}$$

$$m_{top} = 172.5 \text{ GeV}$$
* measure \((tt)/(Z,\gamma \rightarrow ll)\) cross section and trade luminosity uncertainty for theory uncertainty for \(Z,\gamma\) production

\[
\sigma = \frac{N_{\text{obs}} - N_{\text{bg}}}{\varepsilon L}
\]
Top Pair Production Cross Section

- measure \(\frac{\langle tt \rangle}{\langle Z, \gamma \rightarrow ll \rangle}\) cross section and trade luminosity uncertainty for theory uncertainty for \(Z,\gamma\) production

\[
\sigma = \frac{N_{\text{obs}} - N_{\text{bg}}}{\varepsilon L}
\]

(proton

antiproton

\(q\)

\(\bar{q}\)

\(g\)

\(\bar{g}\)

\(t\)

\(\bar{t}\)

\(\gamma\rightarrow ll\)

Luminosity

(proton

antiproton

\(q\)

\(\bar{q}\)

\(Z^0\)

\(e^+\)

\(e^-\)

Luminosity

\(N_{\text{obs}}\)

\(N_{\text{bg}}\)

\(\varepsilon\)

\(L\)
Top Pair Production Cross Section

\[ \sigma_{tt} = 7.82 \pm 0.38 \text{ (stat)} \pm 0.37 \text{ (syst)} \pm 0.15 \text{ (Z theory)} \text{ pb} \]

\[ m_{\text{top}} = 172.5 \text{ GeV} \pm 7\% \]

\[ \sigma_{tt} = 7.32 \pm 0.36 \text{ (stat)} \pm 0.59 \text{ (syst)} \pm 0.14 \text{ (Z theory)} \text{ pb} \]

\[ m_{\text{top}} = 172.5 \text{ GeV} \pm 10\% \]

to be compared to Tevatron goal of \( \pm 10\% \)...
Top Pair Production Cross Section

topological information

\[ \sigma_{\ell\ell} = 8.23 \pm 0.52 \text{ (stat)} \pm 0.83 \text{ (syst)} \pm 0.61 \text{ (luminosity) pb} \]

\[ m_{\text{top}} = 172.5 \text{ GeV} \pm 13\% \]

achieving good precision (~340 events)

b-tagging

\[ \sigma_{\ell\ell} = 7.40 \pm 0.58 \text{ (stat)} \pm 0.63 \text{ (syst)} \pm 0.45 \text{ (luminosity) pb} \]

\[ m_{\text{top}} = 172.5 \text{ GeV} \pm 13\% \]
Top Pair Production Cross Sections

**DØ Run II** *= preliminary*

<table>
<thead>
<tr>
<th>Channel</th>
<th>Cross Section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l+\text{jets}$ (topological)*</td>
<td>$7.25 \pm 0.33 \pm 0.51 \pm 0.49 \pm 0.33 \pm 0.39 \pm 0.43$</td>
</tr>
<tr>
<td>$l+\text{jets}$ (b-tagged)*</td>
<td>$7.93 \pm 0.30 \pm 0.89 \pm 0.54 \pm 0.30 \pm 0.77 \pm 0.47$</td>
</tr>
<tr>
<td>$l+\text{jets}$, dilepton, $\tau+\text{lepton}$ (PRD)</td>
<td>$7.84 \pm 0.45 \pm 0.66 \pm 0.54 \pm 0.45 \pm 0.54 \pm 0.46$</td>
</tr>
<tr>
<td>dilepton (topological)*</td>
<td>$8.23 \pm 0.52 \pm 0.85 \pm 0.65 \pm 0.51 \pm 0.80 \pm 0.67$</td>
</tr>
<tr>
<td>$l+\text{track}$ (b-tagged)*</td>
<td>$5.0 \pm 1.6 \pm 0.9 \pm 1.4 \pm 0.8 \pm 0.3$</td>
</tr>
<tr>
<td>$\tau+\text{lepton}$ (b-tagged)*</td>
<td>$7.32 \pm 1.34 \pm 1.20 \pm 1.24 \pm 1.06 \pm 0.46$</td>
</tr>
<tr>
<td>$\tau+\text{jets}$ (b-tagged, PRD)</td>
<td>$6.30 \pm 1.15 \pm 0.72 \pm 1.09 \pm 0.87 \pm 0.40$</td>
</tr>
<tr>
<td>alljets (b-tagged, PRD)</td>
<td>$6.9 \pm 1.3 \pm 1.4 \pm 1.3 \pm 1.4 \pm 0.4$</td>
</tr>
</tbody>
</table>

$m_{\text{top}} = 175$ GeV CTEQ6.6M

**NEW**

All channels measured except for $\tau_{\text{had}}$ and $\tau_{\text{had}}$

**Combination:**

$\sigma_{t\bar{t}} = 7.50 \pm 0.31 \text{ (stat)} \pm 0.34 \text{ (syst)} \pm 0.15 \text{ (Z theory/lumi)}$ pb

$m_{\text{top}} = 172.5$ GeV ± 6%

⇒ good agreement with SM in all channels
Top Pair Production + Jet Cross Section

important test of NLO QCD, performed for the first time

\[ \sigma_{tt+jet} = 1.6 \pm 0.2 \text{ (stat)} \pm 0.5 \text{ (syst) pb} \]

NLO QCD: \[ \sigma_{tt+jet} = 1.79^{+0.16}_{-0.31} \text{ pb} \]

⇒ good agreement with NLO QCD prediction
Differential Cross Section

- important test of NLO QCD
- unfolding of distributions using regularized method


- need NLO QCD to describe normalisation correctly
Differential Cross Section

- important test of NLO QCD
- unfolding of distributions using regularized method


need NLO QCD to describe normalisation correctly
Differential Cross Section

- important test of NLO QCD
- unfolding of distributions using regularized method

need NLO QCD to describe normalisation correctly

no deviation from the SM

Differential Cross Section

- important test of NLO QCD
- unfolding of distributions using regularized method


Ahrens, Ferroglia, Neubert, Pecjak, Yang

need NLO QCD to describe normalisation correctly

no deviation from the SM

NLO+NNLL: improvement
strong production

- top pair production cross section
- searches for new physics

electroweak production

- single top production cross section
- searches for new physics

conclusions
Search for New Physics in Top Production
Search for $t\bar{t}$ Resonances

- no resonance production in $t\bar{t}$ system is expected in SM
- some models predict $t\bar{t}$ bound states: e.g. leptophobic $Z'$ with strong 3rd generation coupling

$Z'$

- search for bumps in $t\bar{t}$ reconstructed mass spectrum

$t\bar{t}$ reconstructed mass spectrum

- $l+\text{jets}$, $3.6 \text{ fb}^{-1}$
  - $M_{Z'} > 820 \text{ GeV}$

- $l+\text{jets}$, $4.8 \text{ fb}^{-1}$
  - $M_{Z'} > 900 \text{ GeV}$
Outline

strong production

top pair production cross section

searches for new physics

electroweak production

single top production cross section

searches for new physics

conclusions
Single Top Quark Production

**direct measurement of** \(|V_{tb}|\)

**s-channel:** \(\sigma_{tb} = 1.04 \pm 0.04 \, \text{pb}\)

NNNLO \(_{\text{approx}}, m_{top} = 172.5 \, \text{GeV}\)

**t-channel:** \(\sigma_{tb} = 2.26 \pm 0.12 \, \text{pb}\)

NNNLO \(_{\text{approx}}, m_{top} = 172.5 \, \text{GeV}\)

\[ V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \]

- jets
- lepton
- missing \(E_T\)
- b-jets
It has been challenging for years

⇒ multivariate analysis techniques
strong production

top pair production cross section

searches for new physics

electroweak production

single top production cross section

searches for new physics

conclusions
Multivariate Analyses

- Boosted Decision Trees
- Boosted Neural Networks
- Matrix Elements

Combine up to 12 different analysis channels:

DØ Single Top 2.3 fb\(^{-1}\)

Event Yield

Discriminant Output

Single top
Boosted Decision Trees

Neural Networks

Matrix Elements

Likelihood

Multivariate Analyses

combine up to 8 different analysis channels:

**single top**

$E_T^{+}$+jets selection:
recover badly reconstructed e, μ; include τ

CDF Run II Preliminary, $L = 3.2$ fb$^{-1}$

- Single Top
- W+HF
- $t\bar{t}$
- QCD+Mistag
- Other
- Data
Single Top Observation

![Graph showing single top production with 5.0σ significance](image)

<table>
<thead>
<tr>
<th>Single Top Cross Section</th>
<th>Signal Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DØ</strong> 2.3 fb⁻¹ arXiv:0903.0850</td>
<td>3.94 ± 0.88 pb</td>
</tr>
<tr>
<td><strong>CDF</strong> 3.2 fb⁻¹ arXiv:0903.0885</td>
<td>2.3 ± 0.6 pb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Expected</strong></th>
<th><strong>Observed</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 σ</td>
<td>5.0 σ</td>
</tr>
<tr>
<td>&gt;5.9 σ</td>
<td>5.0 σ</td>
</tr>
</tbody>
</table>

\[ |V_{tb}| = 1.07 ± 0.12 \]

\[ |V_{tb}| = 0.91 ± 0.13 \]
Tevatron Single Top Cross Section

$|V_{tb}| = 0.88 \pm 0.07$

⇒ good agreement with SM in all channels

arXiv:0908.2171 [hep-ex]
$\sigma(t\text{-channel}) = 3.14^{+0.94}_{-0.81} \text{ pb}$

evidence with $4.8\sigma$

$\Rightarrow$ good agreement with SM prediction

$\sigma_{t\text{-channel}} = 3.14^{+0.94}_{-0.81} \text{ pb}$

evidence with $4.8\sigma$

$\sigma_{s\text{-channel}}$

evidence with $4.8\sigma$

$\Rightarrow$ good agreement with SM prediction

---

1. N. Kidonakis, PRD 74, 114012 (2006)
2. T. Tait and C.-P. Yuan, PRD 63, 014018 (2001)
Outline

strong production

Top pair production cross section

searches for new physics

electroweak production

Single top production cross section

searches for new physics

conclusions
Flavor Changing Neutral Currents

\[ \kappa_{tgu} , \kappa_{tgc} \]

\[ \frac{1}{\Lambda} < 0.013 \text{ TeV}^{-1} \]

\[ \frac{1}{\Lambda} < 0.057 \text{ TeV}^{-1} \]

at 95% C.L.

arXiv:1006.3575 [hep-ex]
strong production
top pair production cross section
searches for new physics
electroweak production
single top production cross section
searches for new physics
conclusions
Conclusions

**Highlights of top quark physics:**

- **top pair production**
  6% precision, many channels analyses, differential cross section, all good agreement with NLO QCD predictions

- **single top observation + direct measurement of** $V_{tb}$

- **searches for new physics in top sector**
  general agreement with SM

- **precision measurements (see next talk)**
  e.g. top mass

- **top properties (see next talk)**
  new analyses possible such as spin correlation

- **excellent prospects for top quark physics at the Tevatron and the LHC**
Backup
The Tevatron at FERMILAB: pp Collisions

- p source
- Booster
- Tevatron
- Main Injector & Recycler
- CDF
- DØ
- 60 km
- 10^{-12}s after big bang!

√s = 1.96 TeV
Δt = 396 ns

Run I 1987 (92)-95
Run II 2001-11: 100x larger dataset at increased energy
Tevatron Integrated Luminosity

Run II Integrated Luminosity

19 April 2002 - 18 July 2010

Delivered
Recorded

Luminosity (fb)

0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0

peak luminosity of $4.0 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

took many years to achieve this!
Top Pair Production Cross Sections

Good agreement with SM in all channels

All channels measured except for \( \tau \) had \( \tau \) had combination: \( \pm 6\% \)

⇒ good agreement with SM in all channels