Top Production at the Tevatron

Daniel Wicke
(Johannes Gutenberg-Universität Mainz)
for the CDF and DØ collaborations

Outline

• Introduction
• Top pair production
• Single top production
**Introduction**

**The Top Quark**

- Discovered by CDF and DØ in 1995.
- Completes set of quarks in SM.
- Quantum numbers as for up-type quarks.
- Production and decay properties fully determined within SM.
- Mass is the only free parameter

_Proving these properties establishes the SM top quark; Disproving them yields new physics_
The $p\bar{p}$ Accelerator Tevatron

- Circumference 6.4 km.

- $p\bar{p}$ collisions

- Run I (1987-1995)

- Run II (since 2001)
  Collision energy 2 TeV

- 2 experiments, CDF and DØ, record events.

$\mathcal{L} \sim 7 \text{ fb}^{-1}$ on tape.
Today: upto $\sim 4.8 \text{ fb}^{-1}$
Top Quark Production at the Tevatron

Strong top production

$$85\% \quad q\bar{q} \rightarrow t\bar{t}$$
$$15\% \quad gg \rightarrow t\bar{t}$$

$$\sigma(t\bar{t}) \simeq 7.46\text{pb}$$

Moch and Uwer; $$m_t = 172.5 \text{ GeV}$$
PRD 78, 034003 (2008)

Weak top production

Drell-Yan

$$s$$-channel

$$\sigma(t) = 3.46\text{pb} = 1.12\text{pb} + 2.34\text{pb}$$

Kidonakis; $$m_t = 170 \text{ GeV}$$
PRD 74, 114012 (2006)

Per integrated luminosity of $$\sim 1 \text{ fb}^{-1}$$
around 7000 top pairs and 3500 single tops expected.
Top Quark Decay

Top quarks decay to $bW$ (nearly) 100%.

Pair Production Signatures

Decay modes are defined by $W$-decays:

- Dilepton: $(2b + 2l + 2\nu)$
- Lepton+jets: $(2b + 2q + l\nu)$
- Alljets: $(2b + 4q)$

Single Top Signatures

Defined by $W$-decays and channel; e.g. leptonic decay:

- $s$-channel: $(2b + l + \nu)$
- $t$-channel: $(b + q + l + \nu)$
Top Quark Pair Production

Dominant backgrounds

Same signature / jets faking $\ell$ or $E_T$

- Multijet events
  ($q\bar{q}$ or $gg$ + gluon radiation)
- $W$+jets
- $Z$+jets

the “+jets” helps suppression.

Simulation of multijet events
and of fake rates difficult/unprecise

$\Rightarrow$ Estimation from data.

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La Thuile, 4th Mar. 2010
Top Cross-section over $Z$ Cross-section (CDF: $4.6/4.3 \text{ fb}^{-1}$)

In $\ell+\text{jets}$ channel luminosity uncertainty dominating $\Rightarrow$ measure ratios.

**Top Pair**

Isolated $e$ or $\mu$, $E_T$ and $\geq 3$ jets

a) with identified $b$-jet:
   Backgrounds from data before tagging

b) with topological neural net:
   Backgrounds from fit to neural net shapes

**Z Boson**

- Dilepton events with $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$

**Results**

Use theory $Z \rightarrow \ell\ell$ cross-section

a) $\sigma_{Z \rightarrow \ell\ell}/\sigma_{t\bar{t}} = 35.7 \Rightarrow \sigma_{t\bar{t}} = 7.14 \pm 0.35_{\text{(stat)}} \pm 0.58_{\text{(syst)}} \pm 0.14_{\text{(theory)}} \text{pb}$

b) $\sigma_{Z \rightarrow \ell\ell}/\sigma_{t\bar{t}} = 33.0 \Rightarrow \sigma_{t\bar{t}} = 7.63 \pm 0.37_{\text{(stat)}} \pm 0.35_{\text{(syst)}} \pm 0.15_{\text{(theory)}} \text{pb}$

No luminosity uncertainty; 7.0% total uncertainty
Top Cross-section in Alljets Channel (DØ: 1.0 fb$^{-1}$)

- Select 6-jet events with 2 $b$-tags
- Background model

  - from 4 and 5 jet events adding one jet
  - validated by comparing 4 + 1 to 5-jet

- Cross-section from fit to likelihood

  \[
  \sigma_{tt} = 6.9 \pm 1.3(\text{stat}) \pm 1.4(\text{syst}) \pm 0.4(\text{lumi}) \text{pb}
  \]
Overview of Cross-section Results

- Efficiencies depend on top mass
- Results given for $m_t = 172.5$ GeV (CDF) and $m_t = 175$ GeV (D0)
- Good agreement between channels

CDF

Reached 6.5% total uncertainty

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La Thuile, 4th Mar. 2010
Top mass from cross-section (DØ: 1 fb$^{-1}$)

- $\sigma_{t\bar{t}}$ depends on the top mass.

- Both the theoretical prediction and the experimental measurements.

- $l$+jets, dilepton & $\tau$+lepton: $m_t^{\text{Pole}} = 169.1^{+5.9}_{-5.2}$ GeV

![Graph showing the cross-section dependence on top mass](image)

Larger uncertainty, consistent with direct results (see G. Compostella)
Resonant Top Pairproduction

No resonant top production in SM

Some models contain heavy resonances with decay to $t\bar{t}$

Visible in invariant mass $\frac{d\sigma}{dM_{t\bar{t}}}$

Search for narrow resonances

• $D\bar{O}$: $M_{t\bar{t}}$ from direct reconstruction
• No significant deviations.
• Limits on $\sigma_X B(X \rightarrow t\bar{t})$.

E.g. topcolor-assisted technicolor:

$D\bar{O}$: $M_{Z'} > 820$ GeV (expected 870 GeV)

(D$\bar{O}$: $L = 3.6$ fb$^{-1}$; CDF with 2.8 fb$^{-1}$: $M_{Z'} > 805$ GeV)
Unfolded Differential Cross-section (DØ: 1.0 fb⁻¹)

- $\ell$+jets events with at least one $b$-tag
- Kinematic fit used to reconstruct top quark $p_T(t)$
  - Constraints: $2 \times W$-mass, and $m_t = m_{\bar{t}}$
  - Use best jet-parton assignment with best $\chi^2$
- Background is subtracted
  - $W$+jets measured in events “before” $b$-tagging
- Regularised unfolding applied to determine $\frac{d\sigma}{dp_T}$

Approx. NNLO and MC@NLO show best agreement

Pythia and Alpgen get observed the shape at high-$p_T$
Single Top Quark Production

\[ \sigma_{t\bar{t}} = \frac{N - B}{\varepsilon L \cdot BR} \]

Physics background
- Multijet \((q\bar{q} \text{ or } gg + \text{gluon rad.})\)
- \(W+\text{jets}\)
- \(Z+\text{jets}\)

Instrumental background
- Physics object misidentification
- Mismeasurement of energies

Small, but amplified by cross-section.
Single Top Selections

D0 (as an example) requires a lepton, $\not{E}_T$, 2-4 jets at least one identified $b$-jet:

![D0 Single Top 2.3 fb$^{-1}$ Signals and Backgrounds](image)

- Signal to Background after selection 1 : 10 at best.
- Both experiments employ multivariate techniques
Each analysis provides a separate measurement of the single top cross-section
Different multivariate techniques “find” different single top events
Combination of these analyses improves the significance
**Single Top Cross-Section Result**

- CDF&DØ observe single top with $5.0\sigma$ significance
- Measured cross-sections agree at $1.6\sigma$ level
- Since last year new channels were added:

### Single Top Quark Cross Section

<table>
<thead>
<tr>
<th>Channel</th>
<th>L (fb$^{-1}$)</th>
<th>Cross Section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DØ</strong> Lepton+jets</td>
<td>2.3</td>
<td>$3.94^{+0.88}_{-0.88}$</td>
</tr>
<tr>
<td><strong>DØ</strong> Tau+jets</td>
<td>4.8 Preliminary</td>
<td>$3.4^{+2.0}_{-1.8}$</td>
</tr>
<tr>
<td><strong>CDF</strong> Lepton+jets</td>
<td>3.2 Preliminary</td>
<td>$2.17^{+0.56}_{-0.55}$</td>
</tr>
<tr>
<td><strong>CDF</strong> MET+jets</td>
<td>2.1</td>
<td>$5.0^{+2.6}_{-2.3}$</td>
</tr>
<tr>
<td><strong>Tevatron Combination</strong></td>
<td>Preliminary</td>
<td>$2.76^{+0.58}_{-0.47}$</td>
</tr>
</tbody>
</table>

$m_{top} = 170$ GeV

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Single Top in $\tau+$jets (DØ: $4.8 \text{ fb}^{-1}$)

- Identify hadronic $\tau$ with boosted decision trees
- Based on track quantities, calorimeter energies and shower shapes motivated by
  a) $\tau \rightarrow \pi^{\pm} + \nu_{\tau}$
  b) $\tau \rightarrow \rho^{\pm} + \nu_{\tau}$
  c) $\tau \rightarrow 3\pi^{\pm} + \nu_{\tau}(+\pi^{0})$

- Training samples constructed from data
- $\tau$ selection efficiency: 59...76% at 98% rejection

Then BoostedDT single top analysis performed:
- Sensitivity: 1.8$\sigma$
- Observed: $\sigma(t) = 3.4^{+2.0}_{-1.8}\text{ pb}$
**Interpretation as $V_{tb}$**

Assuming SM couplings $V_{tb}$ can be derived:

CDF & D0 combined $|V_{tb}| = 0.88 \pm 0.07$

Reduction to physical range yields

$|V_{tb}| > 0.77$ at 95% C.L.

*with no assumption on the number of generations.*

Reminder:
In top pair production *for three generations* $|V_{tb}| > 0.88$ can be achieved.
Two Dimensional Results and $t$-Channel Measurement

- $s$- and $t$-channel can be fitted simultaneously
- Results consistent with SM at $1 - 2\sigma$-level

- D0 with specialised $t$-channel discriminant: $\sigma_{t\text{-channel}}(t) = 3.14^{+0.94}_{-0.80}$ pb ($4.8\sigma$)
Polarisation of Top Quark

- Polarisation might change in presence of non-SM contributions
- Consider production with right-handed coupling (keeping SM left-handed decay)
- Exotic case changes angle between lepton and jet.
- Train discriminants for SM and exotic (RRLL) separately
- Measure two cross-sections: $\sigma_R$ and $\sigma_L$:

$$\mathcal{P} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1.0^{+1.5}_{-0}$$

In agreement with pure SM production
Summary

- Presented new and updated measurements related to top quark production
- CDF and D0 have analysed up to $4.8 \text{ fb}^{-1}$ of their data

Strong/Double Top
- Discussed various background estimates from data
- Precision reached on cross-section 6.5%
- Properties of top production explored

Electroweak/Single Top
- Observed at $5\sigma$ significance (LaThuile 2009)
- New channels are being explored
- Used to verify properties: $|V_{tb}|$, polarisation, . . .

- No sign of new physics till here
  (G. Compostella will present remaining properties)