Top Quark Production and Properties at the Tevatron (Excluding Top Mass)

Frank Fiedler, LMU München
on behalf of the CDF and DØ Collaborations

Les Rencontres de Physique de la Vallée d’Aoste,
27. 2. - 5. 3. 2005

Overview:

- Introduction: top quarks at the Tevatron
- The total $t\bar{t}$ production cross-section
- Further $t\bar{t}$ measurements
- Single top quark production
- Conclusions

many Tevatron Run II results are preliminary!
updates imminent for most of the measurements!
Why Study the Top Quark?

Its mass makes the top quark special among the fermions

- see George Velev’s talk on top mass measurements

Questions to ask the top quark:
“Do you really behave (only) like the Standard Model top quark?”
“If so, what can you tell us about the Standard Model?”

Obtaining answers:
Tevatron experiments CDF & DØ: currently the only experiments where the top quark can be studied

- total $t\bar{t}$ production cross-section ($\rightarrow$ test perturbative QCD $\rightarrow$ new physics?)
- differential cross-sections, top quark properties, decay branching ratios, ...
  ($\rightarrow$ new physics in $t\bar{t}$ production / top decay?)
- single top production ($\rightarrow V_{tb}$ / new physics)
Standard Model Top Production at the Tevatron

**Top Pair Production (Strong Interaction)**

Feynman diagrams (LO):

- **Strong Interaction**:
  - \( t \bar{t} \) production
  - Feynman diagrams (LO):
    - \( \sigma \sim 6 \text{ pb} \)
    - \( \sim 85\% \)
    - \( \sim 15\% \)

**Single Top Quark Production (Electroweak Interaction)**

Feynman diagrams (LO):

- **Electroweak Interaction**:
  - Single top quark production
  - Feynman diagrams (LO):
    - \( t \bar{b} + W \) associated production
    - \( \sim 0.12 \text{ pb} \)
    - \( \sim 0.9 \text{ pb} \)
    - \( \sim 1.9 \text{ pb} \)

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Tevatron Data Taking Performance

Tevatron performance

DØ data taking efficiency

~200 pb\(^{-1}\): integrated luminosity used by many analyses

⇒ similar numbers for CDF

⇒ already surpass Run I integrated luminosity by a factor >5

⇒ physics analyses typically use ≤200 pb\(^{-1}\) so far
$t\bar{t}$ Event Topologies (I)

$|V_{tb}| \gg |V_{ts}|, |V_{td}|$

$\Rightarrow \text{Br}(t \rightarrow Wb) \sim 100\%$

topology determined by W decays:

- 5% dilepton events
- 30% lepton+jets events
- 44% hadronic events
- 21% events with $\tau$ leptons
**t\bar{t} Event Topologies (II)**

**Dilepton Events:** 5%
- 2 energetic, isolated leptons of opposite charge
- 2 energetic b jets
- Missing transverse energy

- Lepton(+jets) trigger
  → Small but pure sample

**Lepton+jets Events:** 30%
- 1 energetic, isolated lepton
- 4 energetic jets (of which 2 b jets)
- Missing transverse energy

- Lepton(+jets) trigger
  → Large event sample, still good purity

**Hadronic Events:** 44%
- 6 energetic jets (of which 2 b jets)
- Event balanced in transverse plane
- Only jet based triggers

  → Large background (⇒ b identification!)

**Events with \(\tau\) leptons:** 21%
- Additional neutrino(s) from \(\tau\) decay
- Challenging to reconstruct

  → Interesting for new physics searches
  (e.g. \(t \rightarrow H^+b\))

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Lepton+Jets, CDF Topological Analyses (I)

Event selection:
- 1 lepton
  \((p_T > 20 \text{ GeV})\),
- \(E_T > 20 \text{ GeV}\),
- \(\geq 3\) jets
  \((E_T > 15 \text{ GeV}, |\eta| < 2.0)\)

\(H_T\) distribution, \(\geq 3\) jets:
\[
\sigma(t\bar{t}) = (4.7 \pm 1.6 \pm 1.8) \text{ pb}
\]

NN output distribution, \(\geq 3\) jets:
\[
\sigma(t\bar{t}) = (6.7 \pm 1.1 \pm 1.6) \text{ pb}
\]
• neural network inputs chosen to optimise total error
• both analyses: main systematic error from jet energy scale

analysis using $H_T$ distribution only:

- jet energy scale: ±30%
- total systematic error: ±39%
- statistical error: ±34%

optimised analysis using neural network:

- jet energy scale: ±16%
- total systematic error: ±22%
- statistical error: ±16%
Lepton+Jets, DØ Topological Analysis (I)

Event selection:

- 1 isolated energetic lepton ($p_T > 20$ GeV)
- missing transverse energy ($E_T(e+\text{jets}) > 20$ GeV, $E_T(\mu+\text{jets}) > 17$ GeV)
- at least 4 jets ($E_T > 15$ GeV, $|\eta| < 2.5$)

Determination of the $t\bar{t}$ content:

- avoid dependence on absolute energy scale for first analysis
- construct a likelihood discriminant using angular variables and ratios of energy dependent variables, like:

\begin{align*}
S &= 3/2(\lambda_2 + \lambda_3) \\
\lambda_i: & \text{ eigenvalues of normalised momentum tensor}
\end{align*}

- dijet event $\rightarrow S \sim 0$, isotropic event $\rightarrow S \sim 1$

\begin{align*}
H'_{T2} &= H_{T2}/H_z: \text{ measures event centrality} \\
H_{T2}: & \text{ scalar jet } p_T \text{ sum, excluding leading jet} \\
H_z: & \text{ scalar } |p_z| \text{ sum of jets, lepton, and neutrino}
\end{align*}
Likelihood distributions (separately for e+jets and $\mu$+jets events):

Result (combined):

$$\sigma(t\bar{t}) = (7.2^{+2.6}_{-2.4\text{(stat)}})^{+1.6}_{-1.7\text{(syst)}} \pm 0.5\text{(lumi)}\text{ pb}$$
B Tagging

- every $t\bar{t}$ event contains 2 b-jets ($Br(t \rightarrow Wb) \approx 100\%$ in the SM)
  → improve signal/background ratio by b-tagging:

  - tracks with large impact parameter
  - secondary vertices
    example: DØ event tagging probabilities:
    $\varepsilon(t\bar{t}) \sim 60\%$, $\varepsilon(W+\text{jets}) \sim 4\%$
    (events with $\geq 4$ jets, $\geq 1$ tag)
  - soft leptons (muons) from semileptonic decays
    example: CDF event tagging probabilities:
    $\varepsilon(t\bar{t}) \sim 16\%$, $\varepsilon(W+\text{jets}) \sim 3\%$
    (events with $\geq 3$ jets, $\geq 1$ tag)

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Lepton+Jets, DØ B-Tagging Analyses

- Select events with 1 lepton ($p_T > 20$ GeV), missing $E_T$
  
  $(E_T(e+jets) > 20$ GeV, $E_T(\mu+jets) > 17$ GeV), $n$ jets ($E_T > 15$ GeV), and ...

exactly one secondary vertex tagged jet:

\[
\sigma(t\bar{t}) = (8.2 \pm 1.3^{+1.9}_{-1.6} \pm 0.5) \text{ pb}
\]

\[
\sigma(t\bar{t}) = (7.2^{+1.3}_{-1.2}^{+1.9}_{-1.4} \pm 0.5) \text{ pb}
\]

impact parameter b tagging, similar analysis (158–169 pb$^{-1}$):

tt: 7 pb expected contribution shown

background validation region

signal fit region

DØ Run II Preliminary

\[
\text{no. of tagged events vs jet multiplicity}
\]

background validation region

signal fit region

DØ Run II Preliminary

\[
\text{no. of events vs jet multiplicity}
\]
Lepton+Jets, CDF Vertex B-Tag Analyses

- Select events with 1 lepton ($p_T > 20$ GeV), $\not{E}_T > 20$ GeV, and $\geq 3$ jets ($E_T > 15$ GeV, $|\eta| < 2.0$)
- require at least one secondary vertex tagged jet
- $n_{\text{jet}}$ distribution:

![Graph showing the number of tagged events vs. number of jets in W+jets]

- require exactly one secondary vertex tagged jet
- $t\bar{t}$ fraction from leading jet $E_T$ spectrum
- background shape from data (events w/o b-tag)

**FERMILAB-PUB-04-275-E**

- result (162 pb$^{-1}$):

$$\sigma(t\bar{t}) = (5.6^{+1.2}_{-1.1} +0.9) \text{ pb}$$

**FERMILAB-PUB-04-207-E**

- result (162 pb$^{-1}$):

$$\sigma(t\bar{t}) = (6.0 \pm 1.6 \pm 1.2) \text{ pb}$$

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Lepton+Jets, CDF Analysis, Soft Muon Tagging

- Select events with 1 lepton ($p_T > 20$ GeV), $\vec{E}_T > 20$ GeV, and $n$ jets ($E_T > 15$ GeV, $|\eta| < 2.0$)
- require one jet to be b-tagged by the presence of a soft muon inside a jet from a semimuonic b or c decay

- Result ($200 \text{ pb}^{-1}$):
  \[ \sigma(t\bar{t}) = (5.2^{+2.9+1.3}_{-1.9-1.0}) \text{ pb} \]
Dilepton Analyses (I)

CDF measurements ($\sim 200\text{pb}^{-1}$):

- events with 2 isolated tracks ($p_T > 20\text{ GeV}$), $\not{E}_T > 25\text{ GeV}$, and $n$ jets
  
  2 leptons

  1 lepton + 1 track

- combined result ($200\text{ pb}^{-1}$):
  
  $\sigma(t\bar{t}) = (7.0^{+2.4}_{-2.1}^{+1.6}_{-1.1} \pm 0.4)\text{ pb}$

  *PRL 93, 142001 (2004)*

similar DØ “2 lepton” type measurement ($140–156\text{ pb}^{-1}$):

$\sigma(t\bar{t}) = (14.3^{+5.1}_{-4.3}^{+2.6}_{-1.9} \pm 0.9)\text{ pb}$
Variations of the $t\bar{t}$ dilepton analysis:

- measure $t\bar{t}$, $WW$, and $Z \rightarrow \tau\tau$ production (CDF, $200 \text{ pb}^{-1}$):

- apply b-tagging (DØ, $158 \text{ pb}^{-1}$):

\[ \sigma(t\bar{t}) = (8.6^{+2.5}_{-2.4} \pm 1.1) \text{ pb} \]
\[ \sigma(WW) = (12.6^{+3.2}_{-3.0} \pm 1.2) \text{ pb} \]
\[ \sigma(t\bar{t}) = (11.1^{+5.8}_{-4.3} \pm 1.4 \pm 0.7) \text{ pb} \]
Alljets Analyses

- Need b-tagging + tight kinematic criteria to see a signal:
  - 6 to 8 jets (signal region)
  - no isolated leptons
  - kinematic cuts
  → number of tagged jets:

- ≥6 jets
  - exactly 1 b-tagged jet
  - kinematic neural network
  → second neural network including reconstructed masses:

\[
\sigma(t\bar{t}) = (7.8 \pm 2.5^{+4.7}_{-2.3}) \text{ pb}
\]

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The $t\bar{t}$ Production Cross-Section

- Production cross-section $\sigma(p\bar{p}) \rightarrow t\bar{t} + X$

CDF Run II Preliminary

$\Rightarrow$ all results consistent so far (detectors and SM work ok)
$\Rightarrow$ consistent combination in progress

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Anomalies in $t\bar{t}$ Production? (I)

Measured $t\bar{t}$ production in a large variety of channels
→ Any room for physics beyond the Standard Model?

(I) Model independent analyses:

- Compare cross-sections in different channels (CDF, 125 pb$^{-1}$):
  \[\frac{\sigma(\text{dilepton})}{\sigma(\ell + \text{jets})} = 1.45^{+0.83}_{-0.55}\]

- CDF $t\bar{t}$ dilepton events:
  - look at four kinematic distributions (chosen a priori)
  - three of four distributions look ~ as expected
  - most significant deviation from expectation:
    leading lepton $p_T$ spectrum →

  FERMILAB-PUB-04-396-E:
  - overall 1.0–4.5% compatibility with the SM prediction (193 pb$^{-1}$)

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(II) Model dependent analysis:

- search for $t' \rightarrow Wq$ decays

excess of events at large $H_T$?

limit as a function of assumed t' mass:

CDF Run 2 (195 pb$^{-1}$)

$\sigma(p\bar{p} \rightarrow t't', \ell + \geq 4\text{ jets})$

$95\%$ CL upper limit, $m_{t'}=225$ GeV

Cacciari, et al., NLL resummed

hep-ph/0303085
Expect to see only $t \rightarrow Wb$ decays at the Tevatron
$\rightarrow$ anything else would indicate new physics

(I) Is the “W” we measure the W we expect?
- $W$ helicity measurements
- measurement of $t \rightarrow \tau \nu b$
- search for charged Higgs bosons in top decay

(II) Is the “b” we measure the b we expect?
- measurement of $Br(t \rightarrow Wb)/Br(t \rightarrow Wq)$
(V−A) structure of the weak interaction

⇒ spins of top decay products:

\[ \begin{align*}
\text{b quark:} & \quad \text{top quark:} & \quad \text{W boson:} \\
\Rightarrow & & 0 \\
\Rightarrow & & 0 \\
\Rightarrow & & 0 \\
\Rightarrow & & 0
\end{align*} \]

(spin component along b/W momentum axis)

⇒ SM predictions: fraction of top decays with a...

- longitudinal W boson \( F_0 = \frac{1}{1+2m_W^2/m_t^2} \approx 0.70 \)
- left-handed W boson \( F_- = 1 - F_0 \approx 0.30 \)
- right-handed W boson \( F_+ = 0 \)

⇒ distributions of decay angle \( \theta^* \) in

W rest frame for different W helicities:
W Helicity in Top Decays (II)

Measurement strategies at Tevatron Run II:

- lepton $p_t$ from leptonically decaying W (CDF)
- explicit reconstruction of decay angle $\cos \theta^*$ (CDF & DØ)

CDF Run II measurements:

lepton $p_t$ spectrum:

CDF Run II Preliminary (162 pb$^{-1}$)

$$F_0 = 0.27^{+0.35}_{-0.24}$$

DØ Run I: extended matrix element (cf. $m_t$ measurement) → $F_0 = 0.89^{+0.30}_{-0.34}$(stat) ± 0.17(syst)

$$F_0 = 0.56 \pm 0.31$$
DØRun II measurements:
decay angle, topological selection:

\[ F_+ < 0.24 \text{ at } 90\% \text{ C.L.} \]

CDF Run I measurement:
\[ m_{\ell b} \text{ (similar to } \cos \theta^* \text{)} \& \text{ lepton } p_t: F_+ < 0.18 \text{ at } 95\% \text{ C.L.} \]
Charged Higgs Search

charged Higgs with $m_{H^\pm} < m_t$?

→ subtle changes in event topology according to $H^\pm$ decay:

large $\tan \beta$: $H^+ \rightarrow \tau \nu$  
excess of $\tau$ decays in $t\bar{t}$ events

small $\tan \beta$: \begin{align*}
H^+ &\rightarrow c\bar{s} \\
H^+ &\rightarrow Wb\bar{b}
\end{align*}
2 extra $b$ jets in $t\bar{t}$ events

inputs to CDF analysis:

- $\sigma(t\bar{t} \rightarrow \text{dilepton})$
- $\sigma(t\bar{t} \rightarrow \ell + \text{jets})$
- $\frac{\sigma(t\bar{t} \rightarrow \ell + \tau)}{\text{SM expectation}} < 5.0$ at 95% C.L.
Does the top quark decay to other quarks than b quarks?

- compare $t\bar{t}$ event rates with 0 (CDF only), 1, and 2 b-tagged jets

$$\frac{Br(t \rightarrow Wb)}{Br(t \rightarrow Wq)} = \begin{cases} 
1.11^{+0.21}_{-0.19} \text{(stat + syst)} & \text{CDF, 162 pb}^{-1} \\
0.65^{+0.34}_{-0.30} \text{(stat)}^{+0.17}_{-0.12} \text{(syst)} & \text{DØ, imp. par., 158−169 pb}^{-1} \\
0.70^{+0.27}_{-0.24} \text{(stat)}^{+0.11}_{-0.10} \text{(syst)} & \text{DØ, sec. vtx., 158−169 pb}^{-1}
\end{cases}$$

Note: Cannot measure $|V_{tb}|$ in top decays:

$$\frac{Br(t \rightarrow Wb)}{Br(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = \frac{|V_{tb}|^2}{1} \text{ in the SM}$$

$$= \frac{|V_{tb}|^2}{?} \text{ for } > 3 \text{ generations}$$

⇒ single top production: SM cross-section $\sim |V_{tb}|^2!$

+ sensitivity to new physics...
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Concentrate on \textit{s and t channel production} (t+W not feasible at the Tevatron)

Expected event topology: (only consider \textit{leptonic W decays})

- top decay products: lepton, $E_T$, one energetic b jet
- \textit{s-channel}: another energetic b jet
- \textit{t-channel}: other b jet at large $|\eta|$, low $p_T$
- additional light quark jet

\begin{itemize}
  \item $0.9 \, \text{pb}$
  \item $1.9 \, \text{pb}$
\end{itemize}

Challenge: large W+jets background
Selection of single top events at DØ/CDF:

- energetic isolated charged lepton, $Z \rightarrow \ell\ell$ veto
- missing transverse energy
- 2−4 / 2 jets, at least one b-tagged jet
- $H_T$ cut / reconstructed top mass: $140 < m_{bl\nu} < 210$ GeV
- $Q_{\text{lepton}} \cdot \eta_{\text{b jet}}$ distribution to disentangle s and t channels

Single Top Results

- $\sigma(\text{single top}) < ...$

<table>
<thead>
<tr>
<th>Channel</th>
<th>CDF</th>
<th>DØ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$ channel</td>
<td>13.6 pb</td>
<td>19 pb</td>
</tr>
<tr>
<td>$t$ channel</td>
<td>10.1 pb</td>
<td>25 pb</td>
</tr>
<tr>
<td>$s+t$ channel</td>
<td>17.8 pb</td>
<td>23 pb</td>
</tr>
</tbody>
</table>

$\Rightarrow$ limits from Run II better than from Run I

- compare with expected $t$-channel cross-section of $\sim 1.9 \text{ pb}$:
  $\Rightarrow$ need more integrated luminosity to measure $|V_{tb}|$

- new, refined analyses with more data on their way...

- expect to see (SM) single top production with a few $\text{fb}^{-1}$
  (...hope to find new physics...)

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Conclusions

Top physics at Tevatron Run II:

- **$t\bar{t}$ cross-section** measured in many channels: consistent with SM
  $\rightarrow$ next steps: work on systematic errors (jet energy scale!)
  combination of channels

- **more $t\bar{t}$ measurements:**
  differential cross-sections, $W$ helicity measurements,
  search for rare top decays
  $\rightarrow$ great potential with increasing data samples

- **Single top production** ($\rightarrow |V_{tb}|$):
  Run II limits surpass Run I results
  looking forward to more data, and:
  $\rightarrow$ working towards the discovery of single tops at the Tevatron!

- **Top mass**: see George Velev’s presentation
Backup Slides

... on the following pages ...
optimum choice:

- scalar sum of transverse energies, $H_T$
- aplanarity, $A$
- minimum di-jet mass, $\min(m_{jj})$
- maximum jet rapidity, $\eta_{\text{max}}$
- minimum di-jet separation, $\min(\Delta R_{jj})$
- sum of jet transverse energies excluding the two leading jets, $\sum_{i=3}^{5} E_T^i$
- sum of jet longitudinal momenta divided by sum of jet transverse energies, $(\sum p_z)/(\sum E_T)$
normalised momentum tensor $M_{ij} = \frac{\sum_k p_k^i p_k^j}{\sum_k |p_k|^2}$, eigenvalues: $\lambda_1 \geq \lambda_2 \geq \lambda_3$, $\sum \lambda_i = 1$

- sphericity: $S = 3/2(\lambda_2 + \lambda_3)$
- aplanarity: $A = 3/2 \cdot \lambda_3$
- $H_{T2}' = H_{T2}/H_z$: measures event centrality
  $H_{T2}$: scalar jet $p_T$ sum, excluding leading jet
  $H_z$: scalar $|p_T|$ sum of jet, lepton, and neutrino
- $K_{T_{\text{min}}}'$: measure of minimum relative jet $p_T$
  take the minimum dijet separation, multiply by the smaller of the two jet $E_T$ values
  divide by $E_T(W \rightarrow \ell \nu)$ to reduce jet energy scale dependence
  tends to have small values for main background
select events with 1 lepton, missing $E_T$, and $\geq 3$ jets

- require two jets to be secondary vertex b-tagged
  - reduced systematic error from background cross-sections
  - but b-tagging efficiencies “count twice”

\[
\sigma(t\bar{t}) = (5.4^{+2.4}_{-1.9}(\text{stat})^{+1.1}_{-0.9}(\text{syst})) \text{ pb}
\]

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CDF Analysis Looking for Anomalies in Dilepton Events

Look at four kinematic variables in dilepton events

Quantities chosen a priori:

lepton transverse momentum

\[ T = \int \exp \left\{ -\frac{\left( \vec{E}_T^{\text{predicted}} - \vec{E}_T^{\text{measured}} \right)^2}{2\sigma_T^2} \right\} \, d\vec{E}_T^{\text{predicted}} \]

missing transverse energy

\[ \Delta \phi(\ell, \vec{E}_T) \]