Top quark production and properties from the Tevatron, where else?

Michele Weber, Fermilab
For the D0 and CDF Collaborations
Precision Determination of the Top Quark Mass

Pedro A. Movilla Fernández
Lawrence Berkeley National Laboratory

On behalf of the CDF and DØ Collaborations
Single Top Quark Production at the Tevatron

Aurelio Juste
Fermi National Accelerator Laboratory

OUTLINE

• Motivation
• Experimental Challenge
• Search Strategy
• Results:
  • Evidence for Single Top Quark Production
  • First Direct Measurement of $|V_{tb}|$
• Summary
The top quark
TOP
TURNS
TEN
ELEVEN
TWELVE
The Top Quark in the Standard Model

- Top quark was discovered 1995.
- It is required in the Standard Model (SM) as weak isospin partner of the bottom quark.

- Striking property: top quark mass is surprisingly large!
  - near electroweak symmetry breaking (EWSB) scale
  - Yukawa coupling $\sim 1$

- Higgs boson also required by the SM but not seen as yet.
**Why Measure the Top Quark Mass?**

- **Fundamental parameter**
- **Correlated to other SM parameters via electroweak corrections**

![Diagram showing electroweak interactions](image)

- \( \Delta M_W \propto M_T^2 \)
- \( \Delta M_W \propto \ln M_H \)
- New Physics

**Prediction of the Higgs boson mass.**
- **Constraints for physics beyond the SM.**
- **A key to understand EWSB?**

- **Very active field in Tevatron CDF & DØ collaborations with more than 20(!) different measurements competing on the market.**

Heinemeyer et al., JHEP 0608:052 (2006)

- \( m_{top} \) and \( m_W \) (see C. Hays' talk) currently constrain \( m_{Higgs} \) to \(~35\%\)!
Top quarks exist, what do we do with them?

- W-helicity
- QCD
- Prod. kinematics
- Resonances
- Spin correlation
- Mass
- Charge
- Width
- Lifetime
- $t' 
- |V_{tb}|
- Branching ratios
- Anomalous couplings
- $t \rightarrow H^+ b$
Outline

- Top quark production and identification
- Cross section measurements
- Properties of the top quark
- Wtb: branching ratio, W helicity
- Top and new physics
Top Quark Production

- Tevatron is only existing top production machine.
- Run II (since 2001): \( \sqrt{s} = 1.96 \) TeV
- CDF & D0 experiments have \( \sim 2/\text{fb} \) on tape. Run-II goal: 4-8/\text{fb}.
- Top quarks are mainly produced in pairs via strong interaction:
  \[ \sigma_{tt}(1.96 \text{TeV}) = 6.1\text{pb} \]
- 1 top quark pair each \( 10^{10} \) inelastic collisions...

Tevatron is only existing top production machine.

...a needle in a haystack!
Top quark production

Top quark pair production via **strong** interaction

- **85%**
- $6.7 \text{ pb (1.96 TeV, } m_t=175 \text{ GeV}/c^2)$

N. Kidonakis and R. Vogt,


Single top quark production via **weak** interaction

- See talk by A. Juste
- **s-channel**: $1.0 \text{ pb}$
  - NNNLO, $m_t=175$ GeV
- **t-channel**: $2.2 \text{ pb}$

Top quark decay & identification

$t \rightarrow Wb \approx 100\%$

Need to reconstruct and identify Electrons, muons, jets, b-jets and missing transverse energy
decay products have:
• good angular separation in the lab frame
• high transverse momentum
Top Quark Signature

- SM top quark decays weakly before hadronization:
- W decay determines experimental signature:

(for more on top properties, see M. Weber's talk.)

Top Pair Branching Fractions

- all-jets: 6 jets (2 b) 44%
- τ+jets: 15%
- μ+jets: 15%
- e/μ+jets: 15%
- di-leptons: 2 e/μ
- 2 neutrinos
- 2 b-jets

CDF and DØ have vertex detectors to find displaced vertices from decay of long-lived b-hadrons ...crucial to reduce physics background!

lepton+jets candidate

CDF vertex detector

lepton+jets candidate

l, q
v, q̄
b

BR~99.9%

Top Quark Signature

- SM top quark decays weakly before hadronization:
- W decay determines experimental signature:

(for more on top properties, see M. Weber's talk.)

Top Pair Branching Fractions

- all-jets: 6 jets (2 b) 44%
- τ+jets: 15%
- μ+jets: 15%
- e/μ+jets: 15%
- di-leptons: 2 e/μ
- 2 neutrinos
- 2 b-jets

CDF and DØ have vertex detectors to find displaced vertices from decay of long-lived b-hadrons ...crucial to reduce physics background!

lepton+jets candidate

CDF vertex detector

lepton+jets candidate

l, q
v, q̄
b

BR~99.9%
Challenges of Top Quark Physics

- Requires full detector capabilities
  - tracking, calorimetry, hermeticity
  - secondary vertex finding
- Identification of electrons and muons
  → charged leptons from W decay
- Undetected (“missing”) energy
  → neutrino reconstruction ($p_\nu$ unknown)
- Calorimeter clusters (“jets”)
  → quark reconstruction
- Secondary vertex tagging
  → quark flavor (b or light)
  ... reduces physics background and jet/quark combinatorics

Determination of the jet energy scale (JES):
- Correct jet energies for detector effects, hadronization, multiple interactions, ...
  → momenta of hadronic top decay products

JES known to $\sim 3\%$ → dominant uncertainty in all current top quark mass measurements!
Production cross section

\[ \sigma = \frac{N_{\text{events}} - N_{\text{background}}}{\text{Luminosity} \times \varepsilon} \]

- Test of QCD at high \( Q^2 \)
- Higher cross section than predicted could be a sign of new physics: resonant state \( X \to t\bar{t} \) OR anomalous couplings in QCD?
- Lower cross section could also mean new physics: we make assumptions on the expected decay mode
- Important to measure all decay channels and topologies: different sensitivities to new physics possibilities
- Provides samples for properties measurements
Lepton + jets channel

Golden channel:
manageable backgrounds
branching fraction 29%

Backgrounds:
W+jets
fake leptons in multijets
Lepton-Jets Channel

- 1 e/μ with large $p_T$
- 4 jets with large $E_T$
- Energy imbalance, high missing $E_T$
- 0, 1 or 2 b-tags

Combinatorial quark/jet ambiguity: 12 (0 b-tag), 6 (1 b-tag), 2 (2 b-tags)
Well defined kinematics: neutrino momentum partly derived from missing $E_T$

Dominant background types:
- Wbb, Wcc, Wc
- W+light quarks
- non-W+light quarks (fake b-tags)

“Golden Channel”: Compromise between statistics and purity:
- BR ~ 30%
- S/B=1/4 – 11/1 (depending on b-tag requirement)
Lepton+jets cross section

Combining 1,2 tags; 3, >4 jets; e, μ:

\[ \sigma_{t\bar{t}} = 6.6 \pm 0.9 \text{(stat + syst)} \pm 0.4 \text{(lumi)} \text{ pb} \]

@ \( m_t = 175 \text{ GeV} \)

**Ultra pure top sample:**

≥4 jets, 2 tags

0.6±0.4±0.1 BG expected

19 observed

**PRD 74, 112004 (2006)**
Measurement Strategies

**Template Method (TM)**
- Calculate a per-event observable correlated with $M_{\text{top}}$.
- Compare simulated distributions (for signal+background) with varying $M_{\text{top}}$ with data to obtain $M_{\text{top}}$.
- 2nd variable may be explored for JES determination.
  - computationally simple
    - just one number (for each template variable) per event

**Matrix Element Method (ME)**
- Calculate a per-event probability density (from ME) for sig.+bkg. as function of $M_{\text{top}}$.
- Multiply probabilities to extract most likely $M_{\text{top}}$ (and JES) for whole data sample.
  + per-event probability curve enhances statistical power
    - extremely CPU intensive numerical integration
Matrix Element Method

Maximize mass information by exploring SM predictions for top quark dynamics.

\[ P_{t\bar{t}}(M_{\text{top}}, \text{JES}) = \frac{1}{N_{\text{comb}}} \sum \int d\sigma_{t\bar{t}}(y, M_{\text{top}}) d q_1 d q_2 f(q_1) f(q_2) w(x, y, \text{JES}) \]

- sum over all neutrino solutions/jet-quark combinations
- differential cross section
- phase space
- LO \( tt \) production ME
- proton-parton density functions
- "transfer functions" (link jets to quarks)

Transfer functions are probabilities of a set of variables \( \mathbf{x} \) to be measured given a set of parton level quantities \( \mathbf{y} \):
- hadronization and detector resolution effects
- simplifying assumptions: lepton momenta + jet/lepton angles exactly known

Similar expression for background probability but no \( M_{\text{top}} \) dependence.

\[ W^+ \qquad q \{ \equiv m_w \]

JES is determined "in-situ" using W invariant mass: "Penalty" in probability if JES hypothesis leads to a W mass inconsistent with world average value.

→ Part of JES uncertainty becomes statistical component of top mass uncertainty!
CDF: Matrix Element, Lepton+Jets 955pb$^{-1}$

\begin{equation*}
L(M_{\text{top}}, \text{JES}, C_s) \propto \prod_{i=1}^{\text{events}} \left[ C_s P^{(i)}_{t \bar{t}}(M_{\text{top}}, \text{JES}) + (1 - C_s) P^{(i)}_{\text{bck}}(\text{JES}) \right]
\end{equation*}

\begin{itemize}
    \item $M_{\text{top}}, \text{JES}$ extracted in a 2-D maximum likelihood fit
    \item Result using 167 candidate events (\geq1 b-tag):
        \begin{equation*}
        M_{\text{top}} = 170.8 \pm 1.6\text{ (stat.)} \pm 1.5\text{ (JES)} \pm 1.4\text{ (syst.) GeV}/c^2
        \end{equation*}
    \item ...most precise single top quark mass measurement so far!
    \item In-situ technique greatly reduces JES uncertainty. Will further scale down with integrated luminosity.
\end{itemize}
DØ: Matrix Element, Lepton+Jets 370pb⁻¹

- Similar 2-D Likelihood analysis with in-situ JES calibration.
- Includes also events w/o b-tags.

Result using 175 candidate events (≥0 b-tag):

\[ M_{\text{top}} = 170.3 \pm 2.5 \text{ (stat.)} \pm 3.5 \text{ (JES)} \pm 1.5 \text{ (syst.) GeV} / c^2 \]

- DØ update coming soon!

68% CL. intervall
Di-Lepton Channel

- 2 opp. charged lepton candidates
- 2 high $E_T$ jets
- $\geq 0$ or $\geq 1$ b-tag

**Clean sample but poor statistics:**
- BR $\sim 5\%$
- $S/B \sim 2$ ($\geq 0$ b-tag)
- $S/B \sim 20$ ($\geq 1$ b-tag)

**Small combinatorial ambiguity:** 2 jet-quark assignments

**Under-constrained kinematics:** 2 neutrinos but only one missing energy variable

...requires assumptions of/integration over unmeasurable quantities to solve $M_{top}$

**Major background types:**
- $Z/\gamma^*+2$ jets
- $WW+2$ jets
- $W+3$ jets (fake leptons)
Dilepton cross section

- low BG, but also low branching fraction (4.5%)

Backgrounds:
- WW/WZ, Z/γ* → ττ → ll
- fake MET in DY or fake leptons in multijet

Increase efficiency by requiring one fully reconstructed lepton, and require an additional track

σ_{tt} = 8.6^{+1.9}_{-1.7} \text{(stat)}^{+1.1}_{-1.1} \text{(syst)} \text{pb}

Combined with e-μ (which has both leptons fully reconstructed)

σ_{tt} = 9.0 \pm 1.3 \text{(stat)} \pm 0.5 \text{(syst)} \text{pb}

March 5 2007, 1.1fb⁻¹

370pb⁻¹
Event probability is weighted sum of signal and of three major backgrounds

\[ P_{ij}(x; M_{\text{top}}) = P_s(x; M_{\text{top}})w_s(M_{\text{top}}) + \sum_{b=1}^{3} P_{b}^{(i)}(x)w_{b}^{(i)}(M_{\text{top}}) \]

- signal from LO matrix element
- background, fixed weights \( w_{b}^{(i)} \)

... agree well with data.

- Background probabilities reduce \( M_{\text{top}} \) uncertainty by 15%
- In-situ JES calibration not possible for the signal.
CDF: Matrix Element Method, Di-Lepton, 1030pb$^{-1}$

**Result using 78 candidate events ($\geq 0$ b-tag):**

$$M_{\text{top}} = 164.5 \pm 3.9 \text{ (stat.)} \pm 3.5 \text{ (JES)} \pm 1.7 \text{ (syst.) GeV}/c^2$$

... most precise single di-lepton top quark mass!

**Cross check using 30 candidate events ($\geq 1$ b-tag):**

$$M_{\text{top}} = 167.3 \pm 4.6 \text{ (stat.)} \pm 3.3 \text{ (JES)} \pm 1.9 \text{ (syst.) GeV}/c^2$$

\[ \prod P_{t\bar{t}}(x; M_{\text{top}}) \]

... and 45 more events

slope $< 1$ due to background
Di-lepton template methods handle kinematic ambiguity by assuming values for kinematic variables to extract a $M_{\text{top}}$ solution and assigning weights to different solutions.

**Neutrino Weighting Method:** Assume (scan) neutrino pseudo rapidities $\eta(\nu_1), \eta(\nu_2)$ and $m_t$, and assign a weight to the solution based on the compatibility with the observed missing $E_T$

$$w(m_t) \propto \sum_{\nu \text{ assumptions}} \exp \left( -\frac{(E_x^{\text{miss, calc}}(i) - E_x^{\text{miss, obs}})^2}{2\sigma_{E_x^{\text{miss}}}^2} \right) \exp \left( -\frac{(E_y^{\text{miss, calc}}(i) - E_y^{\text{miss, obs}})^2}{2\sigma_{E_y^{\text{miss}}}^2} \right)$$

$M_{\text{top}}$ templates are formed using sum of weights vs. $m_t$.

- $M_{\text{top}} = 160\text{GeV/c}^2$
- $M_{\text{top}} = 175\text{GeV/c}^2$
- $M_{\text{top}} = 190\text{GeV/c}^2$
**DØ: Template, Di-Lepton 370pb⁻¹**

**Matrix Element Weighting Method:** Assume (scan) over \( m_t \) and at most 4 \( \nu \) solutions (given a \( m_t, m_W \), lepton/quark/missing \( E_T \) configuration), assign a weight based on the compatibility of ME prediction with the observed lepton transverse momenta:

\[
w(m_t) \propto \sum_{\nu \text{ solutions}} \sum_{\text{jets}} f_{\text{PDF}}(x_{q_1}) f_{\text{PDF}}(x_{q_2}) p(E_l^*; m_t) p(E_{l*}; m_t)
\]

\( M_{\text{top}} \) templates are formed using \( m_t \) values which gives maximum weight (“peak mass”).

- Repeat calculations with jet/lepton momenta/missing \( E_T \) randomly smeared within their detector resolutions, solve the equations and average the weights.

\[ M_{\text{top}} = 155 \text{GeV/c}^2 \quad \text{DØ Preliminary} \]

\[ M_{\text{top}} = 175 \text{GeV/c}^2 \quad \text{DØ Preliminary} \]
**DØ: Template, Di-Lepton 370pb\(^{-1}\)**

- \(M_{\text{top}}\) obtained from max. likelihood fit for \(\nu\)-weighting and binned likelihood fit for ME weighting.
- Both results are combined considering correlations.

**Result using 26\(\pm\)36 candidate events (370/pb):**

\[
M_{\text{top}} = 178.1 \pm 6.7 \text{(stat.)} \pm 4.3 \text{(JES)} \pm 2.1 \text{(syst.) GeV/c}^2
\]

**Prel. result using 28 candidate events (835/pb):**

\[
M_{\text{top}} = 171.6 \pm 7.9 \text{(stat.)} ^{+5.1}_{-4.0} \text{(syst.) GeV/c}^2
\]

(\(e\mu\) channel only)

**New: CDF template di-lepton analysis based on 1/fb data set:**
- Makes assumptions about the longitudinal momentum of the \(tt\) system to solve equations (see appendix):

**Result using 64 candidate events (1030/pb):**

\[
M_{\text{top}} = 168.1 ^{+5.6}_{-5.5} \text{(stat.)} \pm 3.2 \text{(JES)} \pm 2.4 \text{(syst.) GeV/c}^2
\]
Under-constrained problem requires assumption for one kinematic variable...here: longitudinal momentum \( P_z \) of \( t\bar{t} \) system

\[
\begin{align*}
\vec{P}_{l_1x} + \vec{P}_{l_2x} &= \vec{E}_{T_x} \\
\vec{P}_{l_1y} + \vec{P}_{l_2y} &= \vec{E}_{T_y} \\
\vec{P}_{l_z} + \vec{P}_{\bar{l}z} &= \vec{P}_{ttz} \\
\vec{P}_t &= \vec{P}_{W^+} + \vec{P}_{W^-} \\
\vec{P}_b &= \vec{P}_b + \vec{P} + \vec{P}_W \\
\vec{P}_l &= \vec{P}_l + \vec{P}_W
\end{align*}
\]

Assume \( P_z(t\bar{t})=0 \), \( \sigma\{P_z(t\bar{t})\}=180\text{GeV}/c^2 \):

No top mass dependence, same for signal and background...derived from MC and lepton plus jets data;

Solve numerically equations within allowed phase space:
For each event, dice 10K times the two b-quark energies, \( E_T\text{(miss)} \), and \( P_z(t\bar{t}) \) around their measured/assumed values within their given resolutions.

Sum up and take the most probable resulting ("raw reconstructed") top quark mass to build the template.

No in-situ JES calibration. 

\[
M_{\text{top}} = 168.1^{+5.6}_{-5.5}\text{(stat.)} \pm 3.2\text{(JES)} \pm 2.4\text{(syst.) GeV}/c^2
\]

No in-situ JES calibration. 

\[
\begin{align*}
\vec{P}_l + \vec{P}_\nu &= \vec{P}_{W^+} \\
\vec{P}_\bar{l} + \vec{P}_\bar{\nu} &= \vec{P}_{W^-}
\end{align*}
\]

\[
\text{CDF Run II preliminary (1.0 fb}^{-1})
\]

\[
\text{Likelihood vs. top mass}
\]

\[
\text{Events (15 GeV/c}^2)\]

<table>
<thead>
<tr>
<th>64 data events</th>
<th>signal+bckg</th>
<th>bckg</th>
</tr>
</thead>
</table>

\[
\begin{align*}
\text{CDF: Template, Di-Lepton, 1030pb}^{-1}
\end{align*}
\]
All-Jets Channel

- Exactly 6 jets with high $E_T$
- Lepton veto
- Low missing $E_T$ significance

- $\geq$1 or 2 b-tags
- Large total transverse energy
- Spherical isotropic event topology

- Large combinatorial ambiguity: 90 (1 b-tag), 24 (2 b-tags)
- Well measurable kinematics, no neutrinos.

- Dominant background types:
  non-W $bb4q$ non-W $6q$ (fake b-tags)

- Additional signal probability cut (from ME calculation) yields $S/B \sim 1/1$ ... very restrictive but usable for $>1/fb$. 

Good statistics but huge background:
- BR $\sim 44\%$
- $S/B \sim 1/23$ (≥0 b-tag)
- $S/B \sim 1/6$ (≥1 b-tag)
All-hadronic cross section

- Large branching fraction (46%)
- Huge multijet background (S/B~1/300)
- Need b-jet tagging

NN-based analysis

\[ \sigma_{\tilde{t}\tilde{t}} = 8.3 \pm 1.0(\text{stat})^{+2.0}_{-1.5}(\text{syst}) \pm 0.5(\text{lumi}) \text{ pb} \]

1.02 fb\(^{-1}\)
CDF: Template Method, All-Jets, 943pb$^{-1}$

- 2-D templates for $M_{\text{top}}$ and JES: Signal from ME, background model from data.
  (0 b-tag sample, has negligible signal)

Signal+background probability densities:

$$P(m_t \mid M_{\text{top}}, \text{JES})$$

$$P(m_W \mid M_{\text{top}}, \text{JES})$$

$L_{1,2 \text{ b-tag}} = L_{(\text{top}) \text{shape}} \times L_{(W) \text{shape}} \times L_{\text{obs}} \times L_{\text{sig}}$

- constrain to number of observed events
- constrain to number of signal events
- constrain to a priori JES

Sample likelihood:

$$L = L_{1 \text{ b-tag}} \times L_{2 \text{ b-tags}} \times L_{\text{JES}}$$

Likelihood is maximized w.r.t:

- $M_{\text{top}}, \text{JES}$
- number of 1(2) b-tagged signal/back. events respecting constraints
  (background fraction poorly known in All-Jets channel!)
First All-Jets result with in-situ JES.

All-Jets channel becomes competitive!

Recent result from “traditional” 1-D template method using a kinematic mass fitter:
- no in-situ JES calibration, no restrictive signal probability cut:

1-D template, 1020pb\(^{-1}\), 772 candidate events (\(\geq 1\) b-tag):

\[ M_{\text{top}} = 174.0 \pm 2.2 \text{ (stat.)} \pm 4.5 \text{ (JES)} \pm 1.7 \text{ (syst.) GeV/c}^2 \]
CDF

= shown in previous slides

**DØ Run II Preliminary**

- **combined (topological)**
  - \( L = 230 \text{ pb}^{-1} \)
  - \( 7.1^{+1.2}_{-1.2} \pm 1.4^{+1.4}_{-1.1} \) pb

- **dilepton (topological)**
  - \( L = 370 \text{ pb}^{-1} \)
  - \( 8.6^{+2.3}_{-2.0} \pm 1.2^{+1.2}_{-1.0} \) pb

- **ltrack/emu combined**
  - \( L = 370 \text{ pb}^{-1} \)
  - \( 8.6^{+1.9}_{-1.7}^{+1.1}_{-1.1} \) pb

- **tau+jets**
  - \( L = 350 \text{ pb}^{-1} \)
  - \( 5.1^{+4.3}_{-3.5} \pm 0.7 \) pb

- **alljets/(vertex tag)**
  - \( L = 410 \text{ pb}^{-1} \)
  - \( 4.5^{+2.0}_{-1.9}^{+1.4}_{-1.1} \) pb

- **l+jets (muon tag)**
  - \( L = 420 \text{ pb}^{-1} \)
  - \( 7.3^{+2.0}_{-1.8}^{+0.0}_{-0.0} \) pb

- **l+jets (vertex tag)**
  - \( L = 420 \text{ pb}^{-1} \)
  - \( 6.6^{+0.9}_{-0.9}^{+0.0}_{-0.0} \) pb

- **l+jets (topological)**
  - \( L = 910 \text{ pb}^{-1} \)
  - \( 6.3^{+0.9}_{-0.8}^{+0.7}_{-0.7} \) pb

- **\( m_t = 175 \text{ GeV/c}^2 \)**

---

Lepton+track in the plot by next week...

Assume \( m_t = 175 \text{ GeV/c}^2 \)

* Dilepton
  - \( L = 750 \text{ pb}^{-1} \)
  - \( 8.3 \pm 1.5^{+1.0}_{-0.5} \pm 0.5 \) pb

* Lepton+Jets: Kinematic ANN
  - \( L = 760 \text{ pb}^{-1} \)
  - \( 6.0^{+0.6}_{-0.3}^{+0.9}_{-0.3} \) pb

* Lepton+Jets: Vertex Tag
  - \( L = 695 \text{ pb}^{-1} \)
  - \( 8.2^{+0.6}_{-0.5}^{+0.9}_{-0.5} \) pb

* Lepton+Jets: Soft Muon Tag
  - \( L = 780 \text{ pb}^{-1} \)
  - \( 7.8^{+1.7}_{-1.0}^{+0.5}_{-0.5} \) pb

* MET+Jets: Vertex Tag
  - \( L = 311 \text{ pb}^{-1} \)
  - \( 6.1^{+1.2}_{-0.9}^{+1.4}_{-0.4} \) pb

* All-hadronic: Vertex Tag
  - \( L = 1020 \text{ pb}^{-1} \)
  - \( 8.3^{+1.0}_{-1.5}^{+2.0}_{-0.5} \) pb

* Combined (old SLT, all-had)
  - \( L = 780 \text{ pb}^{-1} \)
  - \( 7.3^{+0.5}_{-0.6}^{+0.7}_{-0.6} \) pb

---

M. Weber

LaThuile 2007

13
Comparisons

Best individual CDF/DØ results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (GeV/c²)</th>
<th>Uncertainty</th>
<th>% Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>DØ Dilepton</td>
<td>178.1 ± 6.7</td>
<td>±8.3</td>
<td>4.7%</td>
</tr>
<tr>
<td>DØ Lepton+Jets</td>
<td>170.3 ± 2.5</td>
<td>±4.5</td>
<td>2.6%</td>
</tr>
<tr>
<td>CDF Dilepton</td>
<td>164.5 ± 3.9</td>
<td>±5.6</td>
<td>3.4%</td>
</tr>
<tr>
<td>CDF Lepton+Jets</td>
<td>170.8 ± 1.6</td>
<td>±2.5</td>
<td>1.5%</td>
</tr>
<tr>
<td>CDF All hadronic</td>
<td>171.1 ± 3.7</td>
<td>±4.3</td>
<td>2.5%</td>
</tr>
<tr>
<td>Tevatron July’06</td>
<td>171.4 ± 1.2</td>
<td>±2.1</td>
<td>1.2%</td>
</tr>
</tbody>
</table>

ΔM<sub>tot</sub> = 173.4 ± 4.3 GeV/c²

M<sub>top</sub>(all-jets) = 171.3 ± 2.2 GeV/c²

M<sub>top</sub>(di-lepton) = 167.0 ± 4.3 GeV/c²

(status Aug. 2006)

- Combination of best Run-I & II results for each experiment (new CDF All-Jets result not included here):
- Detailed comparison taking correlations between systematic uncertainties into account
- Results from different channels are consistent!
- DØ will present new 1/fb results soon.
Conclusions and Outlook

- Confidence through consistent picture of many excellent top mass determinations.
- Important lesson: JES uncertainty can be greatly reduced by in-situ W calibration.
- CDF&DØ have reached a combined precision of 1.2% (better than Run-IIa goal).

\[ M_{\text{top}} = 171.4 \pm 2.1 \text{GeV}/c^2 \]

- Can reach 1% precision with full Run-II data, may even push to \( \Delta m_{\text{top}} \sim 1 \text{GeV}/c^2 \) (expected after 5-10 years LHC!)

Tevatron might be the lasting legacy for the top quark mass!

(...at least for a while)
Significant improvements w.r.t. Run-I.

Combination of best individual results using BLUE technique: (“Best Linear Unbiased Estimate”, NIM A270 110, A500 391)
- Account for correlations
- Include Run-I results
(New CDF All-Jets result not yet incorporated.)

Decay length technique: systematics uncorrelated with other measurements, promising for LHC (see appendix).

Tevatron combined (status Aug. 2006)

\[ M_{\text{top}} = 171.4 \pm 1.2 \text{(stat.)} \pm 1.4 \text{(JES)} \pm 1.0 \text{(syst.)} \text{ GeV/c}^2 \]

Non-JES will be limiting factor at the end of Run-II (see appendix).
Mass dependence

All cross sections are measured at $m_t=175$ GeV

Dependence on mass is studied both for measurement (detection) and theory (production)
Probing the Wtb vertex

- $t \rightarrow Wb / t \rightarrow Wq$
- $W$ helicity in top events
Probing the assumption $t \rightarrow Wb$

$$R = \frac{Br(t \rightarrow Wb)}{Br(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = 0.9980 \text{ to } 0.9984$$

(True in SM with three quark generations)

Measurement: count b-jets.
The number of b-jets depends strongly on R and the tagging efficiency.

- Result is obtained from a binned maximum likelihood fit to data for $N_{jet} = 3$ and $N_{jet} = 4$
- Simultaneous fit to R and cross section

$Br(t \rightarrow Wb) = 1$ and $\sigma_{tt} = 7 \text{ pb}$
Probing $t \rightarrow Wb$

Also allows for a model independent cross section measurement:

$$\sigma_{t\bar{t}} = 7.9^{+1.7}_{-1.5} \text{ (stat + syst) pb}$$

Assuming CKM unitarity $|V_{tb}| > 0.78$ @ 95% CL

Direct $|V_{tb}|$ measurement with single top → see talk by Juste

$$B = \frac{Br(t \rightarrow Wb)}{Br(t \rightarrow Wq)} = 1.03^{+0.19}_{-0.17} \text{ (stat + syst)}$$

230 pb$^{-1}$

PLB 639, 616 (2006)

PRL 95, 102002 (2005)
Examines the nature of the tWb vertex, probing the structure of weak interactions at energy scales near EWSB.

Stringent test of SM and its V-A type of interaction.

Uses boosted W from top decays.

$$M_{t+b}^2 = \frac{1}{2} \cdot (M_T^2 - M_W^2)(1 + \cos \Psi^I)$$
Results (2 selected)

F+ = 0.056 ± 0.080 (stat) ± 0.057 (syst)
F+ < 0.23 @ 95% C.L.

F0 = 0.59 ± 0.12 (stat) ± 0.07 (syst)
F+ < 0.10 @ 95% C.L.

(CDF Run II Preliminary

L_{int} = 955 pb^{-1}

(PRD 75, 031102(R) (2007))

(Earlier result with 0.7 fb^{-1}:
PRL 98, 072001 (2007))
Main SM production mechanisms at a hadron collider:

- **t-channel ("tqb")**
- **s-channel ("tb")**
- **associated production ("tW")**

**Tevatron (\(\sqrt{s}=1.96\) TeV):**
- \(\sim 2.2\) pb
- \(\sim 1.0\) pb
- \(\sim 0.25\) pb

**LHC (\(\sqrt{s}=14\) TeV):**
- \(\sim 235\) pb
- \(\sim 11\) pb
- \(\sim 95\) pb

- **Not discovered yet.** It has been the subject of intense search at the Tevatron since Run I. Here will discuss the experimental status based on \(\sim 1\) fb\(^{-1}\) of Run II data.

- **Motivation:**
  - Study of the \(tbW\) interaction:
    - Direct measurement of \(|V_{tb}|: \sigma \propto |V_{tb}|^2\)
    - Anomalous couplings
  - Sensitivity to different New Physics:
    - s-channel: \(W', H^+, W_{KK,}\ldots\)
    - t-channel: FCNC interactions, 4\(^{th}\) family,..
  - Top spin physics (~100\% polarized top quark)
  - Develop/exercise techniques to extract small signal in a large background (e.g. Higgs search).
Experimental Signature and Event Selection

- **Experimental signature:**
  - One high $p_T$ isolated lepton (e or $\mu$)
  - High missing transverse energy
  - $\geq 2$ jets ($\geq 1$ b-tag)

<table>
<thead>
<tr>
<th>E_{T}^{miss}</th>
<th>MET $\geq$ 25 GeV</th>
<th>15 $&lt;$ MET $&lt; 200$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>e:</td>
<td>$p_T$ $&gt; 20$ GeV, $</td>
<td>\eta</td>
</tr>
<tr>
<td>$\mu$:</td>
<td>$p_T$ $&gt; 20$ GeV, $</td>
<td>\eta</td>
</tr>
</tbody>
</table>
| Jets        | $= 2$, $p_T^{uncorr}$ $> 15$ GeV, $|\eta| < 2.8$ | 2-4, $p_T$ $> 15$ GeV, $|\eta| < 3.4$
|             |                     | $p_{T,1}$ $> 25$ GeV, $|\eta_1| < 2.5$
|             |                     | $p_{T,2}$ $> 20$ GeV |
| B-jet       | 1 or 2              |                         |

- Experimental signature similar to $t\bar{t}$$\rightarrow$lepton+jets but lower jet multiplicity.
- Main backgrounds: $W$+jets and $t\bar{t}$.
In order to achieve the highest possible sensitivity, analyses underwent careful optimization:

- **Maximize acceptance** (loose lepton identification, low $p_T$ thresholds, wide $\eta$ range, improved $b$-tagging performance,…)

- Include as many channels as possible: DØ: 2-4 jets

- Perform analysis in separate channels since S/B different and combine at the end: DØ: (e, $\mu$) x (2,3,4 jets) x (1,2 tags) = 12

- Develop sophisticated multivariate analysis techniques for best possible signal-to-background discrimination.

- Optimize analysis for combined (tb+tqb) search (also perform separate searches).

### Percentage of single top $tb+tqb$ selected events and S:B ratio

<table>
<thead>
<tr>
<th>Electron + Muon</th>
<th>1 jet</th>
<th>2 jets</th>
<th>3 jets</th>
<th>4 jets</th>
<th>≥ 5 jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 tags</td>
<td>10%</td>
<td>25%</td>
<td>12%</td>
<td>5%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>1:3200</td>
<td>1:3900</td>
<td>1:300</td>
<td>1:270</td>
<td>1:230</td>
</tr>
<tr>
<td>1 tag</td>
<td>8%</td>
<td>21%</td>
<td>11%</td>
<td>5%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>1:100</td>
<td>1:20</td>
<td>1:25</td>
<td>1:40</td>
<td>1:53</td>
</tr>
<tr>
<td>2 tags</td>
<td>3%</td>
<td>2%</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>1:11</td>
<td>1:15</td>
<td>1:38</td>
<td>1:43</td>
<td></td>
</tr>
</tbody>
</table>

### Signal acceptances (including BR)

<table>
<thead>
<tr>
<th></th>
<th>$tb$</th>
<th>$tqb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF (2 jets)</td>
<td>~1.9%</td>
<td>~1.3%</td>
</tr>
<tr>
<td>DØ (2-4 jets)</td>
<td>~3.2%</td>
<td>~2.1%</td>
</tr>
</tbody>
</table>
A number of discriminant variables between signal and background can be identified:

- B-tagging NN
- Reconstructed top mass
- Q(lep)\(\eta\)(untagged jet)
- Top spin-related angular variables
- ....

but no single variable is powerful enough to cut on it.

⇒ Combine a number of variables into a single more powerful discriminant variable by using a multivariate analysis technique.

- Standard Neural Network
- Bayesian Neural Network (*)
- Likelihood Discriminants (*)
- Matrix Element Discriminants
- Boosted Decision Trees

(*) Not discussed in detail
Neural Network Analysis

- Consider 26 kinematic or event-shape variables: b-tagging NN, reconstructed top mass, $Q_x\tau$, etc.
- Three NNs trained for combined $(tb+tqb)$ and separate $(tb$ and $tqb)$ searches.
- Build templates for five categories: signal, $tt$, c-like, b-like and non-W.

**Expected Performance**

<table>
<thead>
<tr>
<th></th>
<th>Median p-value (CDF)</th>
<th>$\sigma_{95}$ (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined search</td>
<td>0.5% (2.6$\sigma$)</td>
<td>2.6 pb</td>
</tr>
<tr>
<td>Separate search</td>
<td>0.4% (2.7$\sigma$)</td>
<td>1.3 pb (tqb)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5 pb (tb)</td>
</tr>
</tbody>
</table>

(\*) Assuming no single top
Matrix Element Discriminants

- Pioneered by DØ in Run I top mass measurement. Now being used in a search.
- Attempt to make an optimal use of the kinematic information in the event.
- **Principle**: compute event probability density for a given hypothesis (e.g. single top) making use of all reconstructed objects in the event (integrate over unknowns).

E.g. 2 jet events: \( \tilde{x} = \{p_1^\mu, p_2^\mu, p_3^\mu\} \)

Only 6 “discriminant variables” used!!

\[
P_i(\tilde{x}) = \frac{1}{\sigma} \int \cdots \int \sum_{\text{comb}} d^n \sigma_i(\tilde{y}) dq_1 dq_2 f(q_1) f(q_2) W(\tilde{x} | \tilde{y})
\]

\[
d^n \sigma_i(\tilde{y}) = \frac{(2\pi)^4}{2s} \left| M_i(\tilde{y}) \right|^2 d\Phi^n(\tilde{y})
\]

Maximize sensitivity by:
- summing over all permutations of jets and neutrino solutions
- allowing better measured events to contribute more (via the transfer function)
- implementing b-tagging information

- **Matrix element discriminant** defined as:

\[
EPD = \frac{b \cdot P_{btag}(\tilde{x})}{b \cdot P_{btag}(\tilde{x}) + b \cdot P_{Wbb}(\tilde{x}) + (1-b) \cdot (P_{Wcc}(\tilde{x}) + P_{Wcj}(\tilde{x}))}
\]

\[
b = \text{b-tagging NN probability (event-by-event)}
\]

\[
D_S(\tilde{x}) = \frac{P_S(\tilde{x})}{P_S(\tilde{x}) + P_{bckg}(\tilde{x})}; \quad S = tb \text{ or } tqb
\]

\[
P_{bckg}^{2j}(\tilde{x}) = c_{Wbb} P_{Wbb}(\tilde{x}) + c_{Wcg} P_{Wcg}(\tilde{x}) + c_{Wgg} P_{Wgg}(\tilde{x})
\]

\[
P_{bckg}^{3j}(\tilde{x}) = P_{Wbb}(\tilde{x})
\]
Matrix Element Analyses

- Consider only 2-jet events.
- Single channel search
  (e+μ, 1 tag and 2 tags combined)
- Combined search based on 1D disc:

- Consider 2-jet and 3-jet events.
- Six separate search channels
  (e, μ) x (2, 3 jets) x (1, 2 tags)
- Combined search based on 2D disc:

**Expected Performance**

<table>
<thead>
<tr>
<th></th>
<th>CDF ME analysis</th>
<th>DØ ME analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>median p-value (CDF)</td>
<td>0.5% (2.6σ)</td>
<td>3.6% (1.8σ)</td>
</tr>
</tbody>
</table>
Boosted Decision Trees Analysis

- Machine learning technique, widely used in social sciences, some use in HEP (e.g. MiniBooNe).
- **Idea**: recover events that fail criteria in cut-based analyses.

Start at first “node” with “training sample” of all signal and background events.
- Select variable and splitting value with best separation to produce two “branches”.
- Repeat recursively at each node. Stop when there is no improvement or too few events are left.
- DT output = “leaf” purity, close to 1(0) for signal(background)
- Improve performance of DT by using “adaptive boosting”, which averages over many trees, diluting the piecewise nature of the DT output.

Consider a total of 49 variables to discriminate between signal and backgrounds.
- Most sensitive variables: \( M(\text{all jets}), M(W,b_1) \) (“top mass”), \( Qx_1, \cos(\text{lepton}, b_1) \) \( |_{\text{top rest-frame}} \)
- Adding more variables does not reduce discrimination.
- Reducing number of variables always reduces sensitivity.
- Same list of variables used for all analysis channels.

Trained 36 sets of trees:
- \((tb+tqb, tb, tqb) \times (e, \mu) \times (1,2,3,4 \text{ jets}) \times (1\text{ tag}, 2\text{ tags})\)
- Signal trained against sum of all backgrounds.
- Combined search \((tb+tqb)\) has best sensitivity.

**Expected Performance**

\[ p\text{-value (DØ)} \]

- Combined search \[ 1.8\% (2.1\sigma) \]
**CDF Results**

**NN analysis**

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

- Normalized to fit result
- CDF II data
- $t\bar{t}$ background
- $c$-like background
- $b$-like background
- non-W background

<table>
<thead>
<tr>
<th>NN output</th>
<th>Events per 0.1 units</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>10</td>
</tr>
<tr>
<td>0.5</td>
<td>15</td>
</tr>
<tr>
<td>0.6</td>
<td>20</td>
</tr>
<tr>
<td>0.7</td>
<td>10</td>
</tr>
<tr>
<td>0.8</td>
<td>5</td>
</tr>
<tr>
<td>0.9</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

**Likelihood Function analysis**

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

- Data
- $s$-channel
- $t$-channel
- $W_{b\bar{b}}$
- Mistags
- Non-W
- $Z_{\ell\ell}$
- Diboson
- Syst. Error

Monte Carlo scaled to data

Events vs. $L_{\text{chan}}$

- Events at 0.1
- Events at 0.2
- Events at 0.3
- Events at 0.4
- Events at 0.5
- Events at 0.6
- Events at 0.7
- Events at 0.8
- Events at 0.9
- Events at 1

**Matrix Element analysis**

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

- Single top
t-like$c$-like$t\bar{t}$Non-W

<table>
<thead>
<tr>
<th>Event Probability Discriminant</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
</tr>
<tr>
<td>0.8</td>
</tr>
<tr>
<td>0.9</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\sigma_{t\bar{t}}$</th>
<th>$\sigma_{tb}$</th>
<th>$\sigma_{tb+q\bar{b}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.7_{-0.7}^{+1.5}$</td>
<td>$0.2_{-0.2}^{+1.1}$</td>
<td>$&lt;2.6 \text{ pb}$ @ 95% CL</td>
</tr>
</tbody>
</table>

**Studies ongoing to quantify compatibility of results.** ME-LF:
- Correlation of fit results: ~53%
- Compatibility of measurement in data: ~4-6%
- Analyzing more data should shed some light.

**EPD**

- Prob(null hyp) = 33.7%
- Prob(signal hyp) = 49.8%

**Observed p-value:** 10% (2.3$\sigma$)
**DØ Results**

**Bayesian NN analysis**

\[ \sigma_{tb+tq} = 5.0 \pm 1.9 \text{ pb} \]

*Observed p-value: 1.15% (2.3\(\sigma\))*

**Matrix Element analysis**

\[ \sigma_{tb+tq} = 4.9^{+1.8}_{-1.5} \text{ pb} \]

*Observed p-value: 0.20% (2.9\(\sigma\))*

**Boosted Decision Trees analysis**

\[ \sigma_{tb+tq} = 4.9 \pm 1.4 \text{ pb} \]

*Observed p-value: 0.034% (3.4\(\sigma\))!!

*Compatibility with SM: 11%*

*hep-ex/0612052*

*Submitted to Phys. Rev. Lett.*

**Evidence for single top production!**
Results from the three analyses are consistent with each other.

Overlap within the subset of 50 highest-discriminant events per analysis: ~50%.

Preliminary estimate of correlation in measured cross section between analyses using pseudo-experiments (incl. syst. uncertainties): ~50%.

Combined cross section and significance will soon become available.
Discoveries...

12 years ago!