Measurements of the Top Quark Mass at the Tevatron

Oleg Brandt for the CDF and DØ collaborations

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Why is $m_{\text{top}}$ so interesting?

- The top is special:
  - Heaviest particle of the SM
  - Yukawa coupling is $\sim 1$
  - $\Gamma_{\text{top}} \ll \Lambda_{\text{QCD}}$
    - $\Rightarrow$ top is the only "bare" quark!
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---

Measurements of Top Quark Properties at the Tevatron

3/11/12
More about the top birth place...

$\sqrt{s} = 1.96$ TeV

Tevatron

$L \sim 10.5 \text{ fb}^{-1} \text{ p.e.}$
Measurements of Top Quark Properties at the Tevatron

The CDF and DØ detectors

<table>
<thead>
<tr>
<th></th>
<th>CDF</th>
<th>DØ</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM calorimeter</td>
<td>14%/√E + 1%</td>
<td>22%/√E + 4%</td>
</tr>
<tr>
<td>Hadronic calorimeter</td>
<td>70%/√E + 5%</td>
<td>68%/√E + 5%</td>
</tr>
</tbody>
</table>
Measurements of Top Quark Properties at the Tevatron

The $t\bar{t}$ event sample

$\nu^+ - W^+ + b - t - q' - q - l^- - \nu^-$
We measure the top mass in $tt$ events:

- **Dilepton channel**: low backgrounds, but underconstrained kinematics for $m_{\text{top}}$ measurement and low rate

- **$l$+jets channel**: good compromise between kinematic reconstruction, high rate, and backgrounds

- **All-hadronic channel**: highest branching ratio, very high backgrounds from QCD multijet production

- **Other orthogonal channels**:
  - MET + jets
  - ...

*Can use $b$-tagging to reduce bgr. contributions*
The measurements shown today are based on:

- Template method
- Matrix Element method
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**Template method:**
- Pick a set of variables $x$ sensitive to $m_{\text{top}}$, e.g. $x = m_{\text{top}}^{\text{reco}}$
- Create “templates” = distributions in $x$ using MC:
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**Template method:**
- Pick a set of variables $x$ sensitive to $m_{\text{top}}$, e.g. $x = m_{\text{top}}^{\text{reco}}$
- Create “templates” = distributions of $x$ using MC:
- Maximise the likelihood of their consistence with the data
- → Advantages:
  - few assumptions
  - fairly straight forward
  - combination of channels easy
The measurements shown today are based on:
- Template method
- Matrix Element method

**Matrix Element method:**
- Calculate probability on an event-by-event basis:
  \[
  P_{\text{evt}}(x, m_{\text{top}}) \propto f P_{\text{sig}}(x, m_{\text{top}}) + (1 - f) P_{\text{bgr}}(x)
  \]
- The clue:
  \[
  P_{\text{sig}}(x, m_{\text{top}}) \equiv \frac{1}{\sigma_{t\bar{t}}(m_{\text{top}})} \int W(x, y) d\sigma_{t\bar{t}}(y, m_{\text{top}})
  \]
  \[
  \propto |M|^2(y, m_{\text{top}})
  \]
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  - The clue:
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    - For each event, we calculate based on its consistency to come from \( t\bar{t} \) production, depending on \( m_{\text{top}} \).
    - Use Transfer Functions \( W(x, y) \) to map parton level quantities \( y \) to reco level quantities \( x \).
  - \( \rightarrow \) Maximal use of stat. information on event-by-event basis!
    - *(Disadvantage: high computational demand)*
Matrix Element method, DØ (3.6 fb⁻¹)
- Define the signal probability for 4-jet events as:

\[
P_{\text{sig}} = \frac{1}{\sigma_{\text{obs}}} \sum_{i=1}^{24} w_i \int \sum_{\text{flavors}} |\mathcal{M}_{ti}|^2 \frac{f'(q_1)f'(q_2)}{\sqrt{\left(\eta_{\alpha\beta}q_1^{\alpha}q_2^{\beta}\right)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\text{JES}}).
\]

Permutation weight, b-tag based
LO Matrix Element, \( \sim m_{\text{top}} \)

Transfer Function \( \sim k_{\text{JES}} \)
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P_{\text{sig}} = \frac{1}{\sigma_{\text{obs}}} \sum_{i=1}^{24} w_i \int \sum_{\text{flavors, } \nu} \left| \mathcal{M}_{tt} \right|^2 \frac{f'(q_1)f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\text{JES}}).
\]

- Jet energy scale (JES) is the largest experimental uncertainty.
  - Determine the JES in situ:
    - Constrain the mass of the dijet system from W decay to \( m_W = 80.4 \) GeV
      - \( \delta_{\text{JES}}(m_{\text{top}}) \approx 2\% \Rightarrow \delta_{\text{JES}}^{\text{in situ}}(m_{\text{top}}) \approx 0.5\% \) (and \( \propto \frac{1}{\sqrt{N}} \))

Permutation weight, b-tag based

LO Matrix Element, \( \sim m_{\text{top}} \)


Transfer Function \( \sim k_{\text{JES}} \)
- **Matrix Element method, DØ (3.6 fb⁻¹)**
  
  - Define the signal probability for 4-jet events as:

    \[
    P_{\text{sig}} = \frac{1}{\sigma_{\text{obs}}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int \sum_{\text{flavors, } n} |M_{ti}|^2 \frac{f'(q_1)f'(q_2)}{\sqrt{(\eta_{\alpha\beta}q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\text{JES}}).
    \]

    

    - **Jet energy scale (JES) is the largest experimental uncertainty.**
      
      - Determine the JES in situ:
        
        - Constrain the mass of the dijet system from W decay to \( m_W = 80.4 \text{ GeV} \)
        
        - \( \delta_{\text{JES}}^{\text{direct}} (m_{\text{top}}) \approx 2\% \rightarrow \delta_{\text{JES}}^{\text{in situ}} (m_{\text{top}}) \approx 0.5\% \)
          
          (and \( \propto \frac{1}{\sqrt{N}} \))

      - **Background probability similar (no \( m_{\text{top}} \) dependence)**
        
        - Use ME for W+4 jets from VECBOS, event-by-event
Main systematic uncertainties:

- Signal modeling: Hadronisation + UE, colour reconnection
- Detector modeling: jet energy resolution, b-JES

Relative uncertainty: 0.9%!

Combine 2.6 fb$^{-1}$ + 1 fb$^{-1}$

$m_t (3.6 \text{ fb}^{-1}) = 174.9 \pm 0.8 \text{(stat)} \pm 0.8 \text{(JES)} \pm 1.0 \text{(syst)} \text{ GeV}$

$m_t = 174.9 \pm 1.5 \text{ (GeV)}$

Measurements of Top Quark Properties at the Tevatron

Phys. Rev. D 84, 032004 (2011)
m_{top} in lepton+jets channel (CDF)

- Similar measurement by CDF, ME technique (5.6 fb^{-1})
  - Leading-order ME is used*
  - Transfer functions similar:
    - In addition, angular resolution of jets included
    - Lepton momentum not included
  - No event-by-event background probability:
    - Background events are accounted for via average likelihood based on artificial NN

Similar measurement by CDF, ME technique (5.6 fb⁻¹)

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- Transfer functions similar:
  - In addition, angular resolution of jets included
  - Lepton momentum not included
- No event-by-event background probability:
  - Background events are accounted for via average likelihood based on artificial NN
- Reduce impact from background contributions and mis-measured signal by requiring log(LH) > 10

**Final result:**

\[ m_t = 173.0 \pm 0.7 \text{(stat.)} \pm 0.6 \text{(JES)} \pm 0.9 \text{(syst.)} \text{ GeV} \]

**Main systematic uncertainties:**
- Signal modeling: MC generator (hadronisation + UE), colour reconnection
- Detector modeling: residual JES, b-JES

Relative uncertainty: 0.7%!
Template method in lepton+jets final states, CDF (8.7 fb⁻¹)

- Reconstruct the event kinematics by minimising:

\[
\chi^2 = \sum_{i=\ell,4jets} \frac{(p_T^{i,\text{fit}} - p_T^{i,\text{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(U_j^{\text{fit}} - U_j^{\text{meas}})^2}{\sigma_j^2}
\]

\[
+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - m_t^{\text{reco}})^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - m_t^{\text{reco}})^2}{\Gamma_t^2}
\]

- Consider jet-parton assignments consistent with b-tagging

CDF Conf-Note 10761 (2012)
**Template method in lepton+jets final states, CDF (8.7 fb\(^{-1}\))**

- **Reconstruct the event kinematics by minimising:**

\[
\chi^2 = \sum_{i=\ell, 4\text{jets}} \left( \frac{p^i_{T,\text{fit}} - p^i_{T,\text{meas}}}{\sigma_i^2} \right)^2 + \sum_{j=x,y} \left( \frac{U^j_{\text{fit}} - U^j_{\text{meas}}}{\sigma_j^2} \right)^2
\]

\[
+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2}
\]

**JES constraint**

\[
+ \frac{(M_{b\nu} - m_t^{\text{reco}})^2}{\Gamma_t^2} + \frac{(M_{b\nu} - m_t^{\text{reco}})^2}{\Gamma_t^2}
\]

**MET constraint**

**\(m_{\text{top}}\) extraction**

- **Consider jet-parton assignments consistent with**
  b-tagging

- **Form templates from:**
  - \(m_t^{\text{reco}}\): best jet-parton ass’t
  - \(m_t^{\text{reco}(2)}\): second-best ass’t
  - \(m_{jj}\): dijet invariant mass

---

CDF Conf-Note 10761 (2012)
Final result:

\[ M_{\text{top}} = 172.85 \pm 0.71 \text{ (stat.)} \pm 0.84 \text{ (syst.) GeV} \]

- Largest syst. uncert.:
  - Signal modeling: MC generator (hadronisation +UE), colour reconnection
  - Detector modeling: residual JES, b-jet energy scale

CDF Conf-Note 10761 (2012)
Template method, all-hadronic, CDF (5.8 fb⁻¹):
- Highest BR from all tt decay channels
- Highly challenging due to immense QCD background:
  - After multijet trigger requirement: S:B ~ 1:1200
**Template method, all-hadronic, CDF (5.8 fb⁻¹):**

- Highest BR from all tt decay channels
- Highly challenging due to immense QCD background:
  - After multijet trigger requirement: S:B ~ 1:1200
- Use multilayered NN (MLPFIT) with inputs:
  - “traditional” selection variables like \( \sum E_T, M_{3j}^{\min}, M_{3j}^{\max} \ldots \)
  - specific variables, e.g. 2\(^{nd}\) moments of jets in \( \eta \) and \( \phi \)
Final result:

\[ M_{top} = 172.5 \pm 1.7 \text{ (stat + JES)} \pm 1.1 \text{ (syst)} \text{ GeV/c}^2 \]

- Largest syst. uncert.:
  - Signal modeling: generator, color reconnection, (bgr.model)
  - Detector modeling: residual JES

Largest contribution to world average after l+jets!
Template method, $4.7 \text{ fb}^{-1}$ (DØ):
- $m_{\text{top}}$ free parameter $\rightarrow$ dilepton events are kinematically underconstrained
- Use the so-called neutrino-weighting algorithm:
  - Postulate eta-distributions of neutrinos from MC
  - Calculate weight distribution vs. $m_{\text{top}}$
  - Use 1$^{\text{st}}$ and 2$^{\text{nd}}$ moment of this distribution to form templates
- Apply in-situ JES calibration from $l+jets$ channel:
  
  $1.013 \pm 0.008(\text{stat})$
- Caveat:
  $k_{\text{JES}}$ can be final state-dependent, so we derive a dedicated response correction
- Final result:

$$m_t = 174.0 \pm 2.4(\text{stat}) \pm 1.4(\text{syst}) \text{ GeV}$$

Measurements of Top Quark Properties at the Tevatron

Total uncertainty below 1 GeV for the first time!!!

\[ m_{\text{top}} = 173.2 \pm 0.6 \text{ (stat)} \pm 0.8 \text{ (syst)} \]

arXiv:1107.5255 [hep-ex]
### Tevatron combined values (GeV/c²)

| In-situ JES | 0.39 |
| aJES        | 0.09 |
| bJES        | 0.15 |
| cJES        | 0.05 |
| dJES        | 0.20 |
| rJES        | 0.12 |
| Lepton p_T  | 0.10 |
| **Signal**  | 0.51 |
| Detector Modeling | 0.10 |
| UN/MI       | 0.00 |
| Background from MC | 0.14 |
| Background from Data | 0.11 |
| Method      | 0.09 |
| MHI         | 0.08 |
| Systematics | 0.75 |
| Statistics  | 0.56 |
| **Total**   | 0.94 |

**Relative uncertainty:** 0.54%
### Measurements of Top Quark Properties at the Tevatron

#### Tevatron combined values (GeV/c^2)

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<td>$m_t$</td>
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In-situ JES calibration ~ $1/\sqrt{N}$

Size of calibration samples ~ $1/\sqrt{N}$

Various signal modeling uncert. ~ $\sqrt{\text{brain effort}}$

Relative uncertainty: 0.54%

Expect this limit to be improved...
- Different mass definitions in fixed order calculations:
  - $m_t^\text{pole}$, $m_t^\overline{\text{MS}}$, $m_t^\text{min subtraction}$, ...
  - What we typically measure in kinematic fits is $m_t^\text{MC}$
    - Theory interpretation difficult
    - Arguably, $m_t^\text{MC}$ closer to $m_t^\text{pole}$
Different mass definitions in fixed order calculations:
- $m^\text{pole}_t$, $m^\text{MS}_t$, $m^\text{min subtraction}_t$, ...
- What we typically measure in kinematic fits is $m^\text{MC}_t$.
- Theory interpretation difficult
  - Arguably, $m^\text{MC}_t$ closer to $m^\text{pole}_t$
- Can measure $m^\text{MC}_t$ or $m^\text{pole}_t$ from comparison with $\sigma^\text{MC}_{tt}$ or $\sigma^\text{pole}_{tt}$!
- Account for the weak dependence of $\sigma^\text{tt}$ on $m^\text{MC}_t$ (acceptance effect)

Different mass definitions in fixed order calculations:

- \( m_t^{\text{pole}}, m_t^{\overline{\text{MS}}}, m_t^{\text{min subtraction}} \), ...

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- Can measure \( m_t^{\text{MC}} \) or \( m_t^{\overline{\text{MS}}} \) or \( m_t^{\text{pole}} \) from comparison with \( \sigma_{tt}^{\overline{\text{MS}}} \) or \( \sigma_{tt}^{\text{pole}} \)!

  Account for the weak dependence of \( \sigma_{tt} \) on \( m_t^{\text{MC}} \) (acceptance effect)

<table>
<thead>
<tr>
<th>Theoretical prediction</th>
<th>( m_t^{\text{pole}} ) (GeV)</th>
<th>( \Delta m_t^{\text{pole}} ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC mass assumption</td>
<td>( m_t^{\text{MC}} = m_t^{\text{pole}} )</td>
<td>( m_t^{\text{MC}} = m_t^{\overline{\text{MS}}} )</td>
</tr>
<tr>
<td>NLO+NNLL [14]</td>
<td>163.0^{+5.1}_{-4.6}</td>
<td>-3.3</td>
</tr>
<tr>
<td>Approximate NNLO [15]</td>
<td>167.5^{+5.2}_{-4.7}</td>
<td>-2.7</td>
</tr>
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</table>


Measurements of Top Quark Properties at the Tevatron
- **CPT** is essential for a *locally Lorentz-invariant QFT*
  - $m_{\text{particle}} \neq m_{\text{antiparticle}} \rightarrow \text{CPT violated!}$
  - Top is the only quark where this test is possible: $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25} \text{ s}$
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- DØ measures directly and independently \( m_t, m_{\bar{t}} \) (ME):

\[
\Delta m \equiv m_t - m_{\bar{t}} = 0.8 \pm 1.8 \text{ (stat)} \pm 0.5 \text{ (syst)} \text{ GeV}
\]
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\]

- CDF measures directly $\Delta m$ with

\[
\frac{m_t + m_\bar{t}}{2} \equiv 172.5 \text{ GeV}
\]

\[
\Delta m = -1.95 \pm 1.11 \text{ (stat)} \pm 0.59 \text{ (syst)} \text{ GeV (8.7 fb}^{-1})
\]
Top quark mass measurement is a Tevatron legacy:

- Many systematic uncertainties generically smaller at the Tevatron compared to LHC:
  - $t\bar{t}$ signal modeling: ISR, kinematics of production
  - Run conditions: more uniform + substantially less pile-up
- $\rightarrow$ we need to capitalise on this
- The Tevatron will provide a substantial contribution to the world average $m_{\text{top}}$ until ILC (uncertainty now: 0.54%)
Summary and outlook

- Top quark mass measurement is a Tevatron legacy:
  - Many systematic uncertainties generically smaller at the Tevatron compared to LHC:
    - tt signal modeling: ISR, kinematics of production
    - Run conditions: more uniform + substantially less pile-up
  - → we need to capitalise on this
  - The Tevatron will provide a substantial contribution to the world average $m_{\text{top}}$ until ILC (uncertainty now: 0.54%)

- We are expecting many more exciting results from the Tevatron and the LHC in the coming years:
  - DØ: [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)

- 15 years after the top quark discovery, the era of precision measurements in the top sector has begun!
Combination of CDF and DØ results on the mass of the top quark using up to 5.8 fb\(^{-1}\) of data

The Tevatron Electroweak Working Group\(^1\) for the CDF and DØ Collaborations

Abstract

We summarize the top-quark mass measurements from the CDF and DØ experiments at Fermilab. We combine published RunI (1992–1996) measurements with the most precise published and preliminary RunII (2001-present) measurements using up to 5.8 fb\(^{-1}\) of data, adding new analyses (the \(E_T+\text{Jets}\) analysis) and updating old ones. Taking uncertainty correlations into account, and adding in quadrature the statistical and systematic uncertainties, the resulting preliminary Tevatron average mass of the top quark is \(M_t = 173.2 \pm 0.9\) GeV/c\(^2\).
Measurements of Top Quark Properties at the Tevatron

ATLAS, CDF, CMS, and DØ

Combination of CDF and DØ results on the mass of the top quark using up to 5.8 fb\(^{-1}\) of data

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... FOR THE TEVATRON (2011)
We are looking ahead to more exciting measurements from the Tevatron!
<table>
<thead>
<tr>
<th>Property</th>
<th>Measurement</th>
<th>SM Prediction</th>
<th>Luminosity (fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)</td>
<td>CDF: $7.5 \pm 0.31$ (stat) $\pm 0.34$ (syst) $\pm 0.15$ (theory) pb</td>
<td>$7.46^{+0.48}_{-0.67}$ pb</td>
<td>up to 4.6</td>
</tr>
<tr>
<td></td>
<td>D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb</td>
<td></td>
<td>5.6</td>
</tr>
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<td>$\sigma_{tbq}$ (for $M_t = 172.5$ GeV)</td>
<td>CDF: $0.8 \pm 0.4$ pb ($M_t = 175$ GeV)</td>
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<td>$\sigma_{tb}$ (for $M_t = 172.5$ GeV)</td>
<td>CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)</td>
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<td>5.4</td>
</tr>
<tr>
<td>Charge asymmetry</td>
<td>CDF: $0.158 \pm 0.074$</td>
<td>0.06</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>D0: $0.196 \pm 0.065$</td>
<td></td>
<td>5.4</td>
</tr>
<tr>
<td>Spin correlation</td>
<td>CDF: $0.72 \pm 0.64$ (stat) $\pm 0.26$ (syst)</td>
<td>$0.777^{+0.027}_{-0.042}$</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>D0: $0.66 \pm 0.23$ (stat + syst)</td>
<td></td>
<td>5.4</td>
</tr>
<tr>
<td>$M_t$</td>
<td>Tev: $173.2 \pm 0.9$ GeV</td>
<td>-</td>
<td>up to 5.8</td>
</tr>
<tr>
<td>$\sigma_{t\bar{t}\gamma}$</td>
<td>CDF: $0.18 \pm 0.08$ pb</td>
<td>$0.17 \pm 0.03$ pb</td>
<td>6.0</td>
</tr>
<tr>
<td>$</td>
<td>V_{tb}</td>
<td>$</td>
<td>CDF: $</td>
</tr>
<tr>
<td></td>
<td>D0: $</td>
<td>V_{tb}</td>
<td>= 1.02^{+0.10}_{-0.11}$</td>
</tr>
<tr>
<td>$R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$</td>
<td>CDF: $&gt; 0.61$ @ 95% CL</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>D0: $0.90 \pm 0.04$</td>
<td></td>
<td>5.4</td>
</tr>
<tr>
<td>$\sigma(gg \rightarrow t\bar{t})/\sigma(p\bar{p} \rightarrow t\bar{t})$</td>
<td>CDF: $0.07^{+0.15}_{-0.07}$</td>
<td>0.18</td>
<td>1</td>
</tr>
<tr>
<td>$M_t - M_{\bar{t}}$</td>
<td>CDF: $-3.3 \pm 1.4$ (stat) $\pm 1.0$ (syst) GeV</td>
<td>0</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>D0: $0.8 \pm 1.8$ (stat) $\pm 0.5$ (syst) GeV</td>
<td></td>
<td>3.6</td>
</tr>
<tr>
<td>$W$ helicity fraction</td>
<td>Tev: $f_0 = 0.732 \pm 0.063$ (stat) $\pm 0.052$ (syst)</td>
<td>0.7</td>
<td>up to 5.4</td>
</tr>
<tr>
<td>Charge</td>
<td>CDF: $-4/3$ excluded @ 95% CL</td>
<td>$2/3$</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>D0: $4/3$ excluded @ 92% CL</td>
<td></td>
<td>0.37</td>
</tr>
<tr>
<td>$\Gamma_t$</td>
<td>CDF: $&lt; 7.6$ GeV @ 95% CL</td>
<td>$1.26$ GeV</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>D0: $1.99^{+0.69}_{-0.55}$ GeV</td>
<td></td>
<td>up to 2.3</td>
</tr>
</tbody>
</table>
The Transfer Functions \( W(x, y; JES) \) map parton-level quantities to reco-level ones.

- Treat separately:
  - Light quark jets
  - \( b \)-tagged jets w/ soft muon tag
  - All other \( b \)-jets
  - \( x \) 4 \(|\eta|\) regions for each
• Behold! We need to calibrate the method:
  - is the extracted central value unbiased?
  - is the statistical uncertainty over/underestimated?
- We are interested in **parton-level quantities** for our top measurements
  - Map the energies of reco-level jets
    - particle jets (D0) / partons (CDF)
  - This is referred to as a Energy Scale (JES) corr’n
  - With the current size of samples:
    - $s(\text{JES})/\text{JES} \sim 1.5\%$ (D0)
    - $s(\text{JES})/\text{JES} \sim 2.5\%$ (CDF)
- And many more:
  - Lepton ID, $p_T$ scale
- **Typical JES uncertainty** 2-3 %
  - Can lead to an uncertainty on $m_{\text{top}}$ as large as 2 GeV!
Play experimental trick:
- Largest experimental uncertainty is the JES:

- Perform an in-situ calibration of the JES:
  - Constrain the two jets from $W$ decay to $m_W$
  - This allows a simultaneous extraction of $m_{top}$ and $k_{JES}$!
<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modeling of production:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Modeling of signal:</strong></td>
<td></td>
</tr>
<tr>
<td>Higher-order effects</td>
<td>±0.25</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>±0.26</td>
</tr>
<tr>
<td>Hadronization and UE</td>
<td>±0.58</td>
</tr>
<tr>
<td>Color reconnection</td>
<td>±0.28</td>
</tr>
<tr>
<td>Multiple $p\bar{p}$ interactions</td>
<td>±0.07</td>
</tr>
<tr>
<td>Modeling of background</td>
<td>±0.16</td>
</tr>
<tr>
<td>$W$+jets heavy-flavor scale factor</td>
<td>±0.07</td>
</tr>
<tr>
<td>Modeling of $b$ jets</td>
<td>±0.09</td>
</tr>
<tr>
<td>Choice of PDF</td>
<td>±0.24</td>
</tr>
<tr>
<td><strong>Modeling of detector:</strong></td>
<td></td>
</tr>
<tr>
<td>Residual jet energy scale</td>
<td>±0.21</td>
</tr>
<tr>
<td>Data-MC jet response difference</td>
<td>±0.28</td>
</tr>
<tr>
<td>$b$-tagging efficiency</td>
<td>±0.08</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>±0.01</td>
</tr>
<tr>
<td>Lepton momentum scale</td>
<td>±0.17</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>±0.32</td>
</tr>
<tr>
<td>Jet ID efficiency</td>
<td>±0.26</td>
</tr>
<tr>
<td><strong>Method:</strong></td>
<td></td>
</tr>
<tr>
<td>Multijet contamination</td>
<td>±0.14</td>
</tr>
<tr>
<td>Signal fraction</td>
<td>±0.10</td>
</tr>
<tr>
<td>MC calibration</td>
<td>±0.20</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>±1.02</td>
</tr>
</tbody>
</table>

- **Modeling of signal:** 0.8 GeV
- **Modeling of detector:** 0.6 GeV
- **Method:** 0.3 GeV
**Final result:**

\[ m_t = 173.0 \pm 0.7 \text{(stat.)} \pm 0.6 \text{(JES)} \pm 0.9 \text{(syst.)} \text{ GeV} \]

**Main systematic uncertainties:**
- Signal modeling: MC generator, colour reconnection
- Detector modeling: residual JES, b-JES

Relative uncertainty: 0.7%!
m_{top} in l+jets + dilepton ch. (CDF)

- **Final result:**

\[ M_{\text{top}} = 172.85 \pm 0.71 \text{ (stat.) } \pm 0.84 \text{ (syst.) GeV} \]

- **Largest syst. uncert.:**
  - Signal modeling: MC generator, colour reconnection
  - Detector modeling: residual JES, b-jet energy (?)

<table>
<thead>
<tr>
<th>Systematic</th>
<th>GeV/c^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual JES</td>
<td>0.52</td>
</tr>
<tr>
<td>Generator</td>
<td>0.56</td>
</tr>
<tr>
<td>Next Leading Order</td>
<td>0.09</td>
</tr>
<tr>
<td>PDFs</td>
<td>0.08</td>
</tr>
<tr>
<td>b jet energy</td>
<td>0.10</td>
</tr>
<tr>
<td>b tagging efficiency</td>
<td>0.03</td>
</tr>
<tr>
<td>Background shape</td>
<td>0.20</td>
</tr>
<tr>
<td>gg fraction</td>
<td>0.03</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.06</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.05</td>
</tr>
<tr>
<td>Lepton energy</td>
<td>0.03</td>
</tr>
<tr>
<td>MHI</td>
<td>0.07</td>
</tr>
<tr>
<td>Color Reconnection</td>
<td>0.21</td>
</tr>
<tr>
<td>Total systematic</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Most precise m_{top} meas’t to date
\[ M_{\text{top}} = 172.5 \pm 1.7 \text{ (stat + JES)} \pm 1.1 \text{ (syst)} \text{ GeV/c}^2 \]

**Final result:**

Largest contribution to world average after l+jets!

- Signal modeling: generator, color reconnection, (bgr.model)
- Detector modeling: residual JES

**Largest syst. uncert.:**

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta M_{\text{top}}^{\text{syst}} ) (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual bias</td>
<td>0.2</td>
</tr>
<tr>
<td>Calibration</td>
<td>0.1</td>
</tr>
<tr>
<td>Generator</td>
<td>0.5</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>0.1</td>
</tr>
<tr>
<td>b-jets energy scale</td>
<td>0.2</td>
</tr>
<tr>
<td>SF ( E_T ) dependence</td>
<td>0.1</td>
</tr>
<tr>
<td>Residual JES</td>
<td>0.4</td>
</tr>
<tr>
<td>PDF</td>
<td>0.2</td>
</tr>
<tr>
<td>Multiple Hadron Interactions</td>
<td>0.1</td>
</tr>
<tr>
<td>Color Reconnections</td>
<td>0.3</td>
</tr>
<tr>
<td>Templates Statistics</td>
<td>0.3</td>
</tr>
<tr>
<td>Background</td>
<td>0.6</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>1.1</td>
</tr>
</tbody>
</table>

CDF Conf-Note 10456 (2010)
- **Powerful tool constructed:**

  ![Graph showing distributions](image)

  - Define control region $N_{out} < 0.25$
    - Derive corrections for tag rate (correl’ns for multiple tags)
Use b-tagging to refine S:B and improve combinatorics:
- 30 jet-parton assignments with 1 b-tag
- 6 assignments with 2 b-tags

For each assignment minimise:

\[
\chi^2 = \frac{(m_{jj}^{(1)} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jj}^{(2)} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jjb}^{(1)} - m_t^{\text{rec}})^2}{\Gamma_t^2} + \frac{(m_{jjb}^{(2)} - m_t^{\text{rec}})^2}{\Gamma_t^2} + \sum_{i=1}^{6} \frac{(p_{T,i}^{\text{fit}} - p_{T,i}^{\text{meas}})^2}{\sigma_i^2}
\]

- Double \( m_W \) constraint for JES
- Constraint on \( m_{\text{top}} \)
- Consistence of fitted 4-momenta with measured ones

Pick assignment with minimal \( \chi^2 \)

Now we are able to reconstruct \( m_{\text{top}} \) and \( m_W \)!
- Select events for the measurement:
  - With $N_{\text{out}} > 0.97$ and $\chi^2 < 2$ for 1 b-tag (S:B ~ 1:3)
  - With $N_{\text{out}} > 0.94$ and $\chi^2 < 3$ for 2+ b-tags (S:B ~ 1:1)

- Maximise binned likelihood for
  - $m_{\text{top}}$, $m_W$, $n_{\text{signal}}$ events, $n_{\text{background}}$ events
Final value after calibration:

\[ M_{\text{top}} = 172.5 \pm 1.7 \text{ (stat + JES)} \pm 1.1 \text{ (syst)} \text{ GeV}/c^2 \]

\[ \Delta \text{JES} = -0.10 \pm 0.3 \text{ (stat + } M_{\text{top}}\text{)} \pm 0.3 \text{ (syst)} \sigma_{\text{JES}} \]

→ Strongest contribution to world average after l+jets!
A bit of history

- 1976: discovery of the Ypsilon at Fermilab
  - indicates the existence of the top quark
  - from here on, the race for the top has begun!

- 1984: PETRA $m_{\text{top}} > 23.3$ GeV

- 1988: UA1 $m_{\text{top}} > 44$ GeV

- 1990:
  - TRISTAN $m_{\text{top}} > 30.2$ GeV
  - SLC $m_{\text{top}} > 40.7$ GeV
  - LEP $m_{\text{top}} > 45.8$ GeV
  - UA1 $m_{\text{top}} > 60$ GeV
  - UA2 $m_{\text{top}} > 69$ GeV

- 1992: CDF $m_{\text{top}} > 91$ GeV

- 1994: DØ $m_{\text{top}} > 128$ GeV

- 1994: evidence of top quark from CDF
Derive a correction for particle jets matched to reconstructed jets in MC:

\[ F^{\text{corr}} = \frac{\sum_i E_i^{\text{true}} \cdot R_i^{\text{data}}}{\sum_i E_i^{\text{true}} \cdot R_i^{\text{MC}}} \]

- Sum runs over all particles
- \( R_i \rightarrow \) single particle response
- \( R_i(\text{particle type}, E_{\text{part}}, \eta_{\text{part}}) \)

Correct the MC:

\[ E_{\text{jet}}^{\text{corr}} = F^{\text{corr}} \cdot (E_{\text{jet}}^{\text{raw}} - E_O) \]
Single particle response correction

Correction for u, d, s, c quark jets

Correction for gluon jets

Correction of b quark jets

$p_T$ (GeV)
- **CPT invariance** is a necessary prerequisite for a locally Lorentz-invariant QFT.
  - An established CPT invariance would be the end of not only the SM itself, but its theoretical footing!

- **If** $M_{\text{particle}} \neq M_{\text{antiparticle}}$ → CPT violated!
  - We have never tested this on a bare quark (status 2yrs ago)

- The top quark is the only known quark where this test is possible:
  - Hadronisation time scale $\gg \tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s
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The top quark is the only known quark where this test is possible:
- Hadronisation time scale $\gg \tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s

First result (D0, 1 fb$^{-1}$):
$$\Delta m_t = 3.8 \pm 3.4(\text{stat}) \pm 1.2(\text{syst}) \text{ GeV}$$

First result from CDF (5.4 fb$^{-1}$):
$$\Delta m_t = -3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst}) \text{ GeV}$$
- $\rightarrow$ 2 SD effect?
In standard pythia, it is impossible to generate $tt$ events with $M_t \neq M_{\bar{t}}$, modify pythia (6.413):
- Allow for separate setting of $M_t$, $M_{\bar{t}}$
- Adjust description of all $M_t$, $M_{\bar{t}}$ related kinematic quantities:
  - e.g. resonance widths $\Gamma_t$, $\Gamma_{\bar{t}}$
- Use standard CTEQ6L1 PDFs at scale:
  \[
  Q^2 = \left( p_T^{\text{scat}} \right)^2 + \frac{1}{2} \left\{ P_1^2 + P_2^2 + M_t^2 + M_{\bar{t}}^2 \right\}
  \]

Measurement of the mass difference between top and antitop quarks

(170,180) GeV  (170,170) GeV
Use the most statistically sensitive technique – ME
- $P(m_{\text{top}}, k_{\text{JES}}) \rightarrow P(m_t, m_{\text{tbar}})$
  - Direct and independent measurement of $m_t$ and $m_{\text{tbar}}$.
- Use lepton charge to tag $t$ and $t\bar{t}$:

$$\Delta m_t = 0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst}) \text{ GeV}$$

Relative precision: 1%
- Lots of work went into evaluating systematics for this precision meas’

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty on $\Delta m$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modeling of detector:</td>
<td></td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.15</td>
</tr>
<tr>
<td>Remaining jet energy scale</td>
<td>0.05</td>
</tr>
<tr>
<td>Response to $b$ and light quarks</td>
<td>0.09</td>
</tr>
<tr>
<td>Response to $b$ and $\bar{b}$ quarks</td>
<td>0.23</td>
</tr>
<tr>
<td>Response to $c$ and $\bar{c}$ quarks</td>
<td>0.11</td>
</tr>
<tr>
<td>Jet identification efficiency</td>
<td>0.03</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.30</td>
</tr>
<tr>
<td>Determination of lepton charge</td>
<td>0.01</td>
</tr>
<tr>
<td>ME method:</td>
<td></td>
</tr>
<tr>
<td>Signal fraction</td>
<td>0.04</td>
</tr>
<tr>
<td>Background from multijet events</td>
<td>0.04</td>
</tr>
<tr>
<td>Calibration of the ME method</td>
<td>0.18</td>
</tr>
<tr>
<td>Total</td>
<td>0.47</td>
</tr>
</tbody>
</table>

$\Delta R = \frac{1}{2} \cdot (p_T^{tag} + p_T^{probe})$

$f_{\Delta R} = 0.0042$
• D0 (50 pb\(^{-1}\), 4.6\(\sigma\)):
  - \(\sigma=6.4\pm2.2\) pb
  - \(m_{\text{top}}=199\pm30\) GeV

• CDF (67 pb\(^{-1}\), 4.8\(\sigma\)):
  - \(\sigma=6.8^{+3.6}_{-2.4}\) pb
  - \(m_{\text{top}}=176\pm13\) GeV

24 Feb. 1995

The birth (1995)
• Tevatron has shown a great performance in FY 2010!
• We keep enlarging our calibration samples
  - Better handles on experimental uncertainties:
    • e.g. Jet Energy Scale (JES), Jet Energy Resolution, etc.

Delivered: 10.5 fb$^{-1}$
Recorded: 9.5 fb$^{-1}$
Data taking eff.: $>90\%$
• **In the SM:**
  - $|V_{tb}| = 0.9990-0.9992$
  - @ 95% C.L. assuming 3 CKM generations

• **Characterise tt final states by top decays!**

---

![Top Pair Branching Fractions](image)

- "alljets" 46%
- $\tau+\text{jets}$ 15%
- $\mu+\text{jets}$ 15%
- $e+\text{jets}$ 15%
- $\tau+\tau$ 1%
- $\tau+\mu$ 2%
- $\tau+e$ 2%
- $\mu+\mu$ 1%
- $\mu+e$ 1%
- $e+e$ 1%

---

**Dilepton**
(BR~5%, low bkg)

**Lepton+jets**
(BR~30%, moderate bkg)

**All-hadronic**
(BR~46%, huge bkg)
### Typical ttbar preselection

<table>
<thead>
<tr>
<th>Dilepton</th>
<th>Lepton+jets</th>
<th>All-hadronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 high-(p_T) leptons</td>
<td>1 high-(p_T) lepton (&gt;20 GeV)</td>
<td>No leptons</td>
</tr>
<tr>
<td>Missing (E_T)</td>
<td>Missing (E_T) (&gt;40 GeV)</td>
<td>No missing (E_T)</td>
</tr>
<tr>
<td>2 jets</td>
<td>4 jets (&gt;20 GeV)</td>
<td>6 jets</td>
</tr>
<tr>
<td>(\geq 0) b-tags</td>
<td>(\geq 1) b-tag</td>
<td>(\geq 1) b-tag</td>
</tr>
<tr>
<td>S/B:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Dilepton**
(BR~5%, low bckg)

**Lepton+jets**
(BR~30%, moderate bckg)

**All-hadronic**
(BR~46%, huge bckg)
The CDF and D0 detectors

| Tracking       | Silicon | $|\eta| < 2 - 2.5$ | Silicon | $|\eta| < 3$ |
|----------------|---------|-----------------|---------|----------|
|                | Drift cell | $|\eta| < 1.1$   | Fiber   | $|\eta| < 1.7$ |
| Calorimetry    | Scintillators | $|\eta| < 3.6$ | LAr/DU  | $|\eta| < 4$ |
| Muon chambers  | Drift Scintillators | $|\eta| < 1.5$ | Drift Scintillators | $|\eta| < 2.0$ |
MuonID @ Highest Luminosities @ DØ

Oleg Brandt, Göttingen/FNAL
The CDF Detector

- Silicon vertex detector
- Tracking chamber
- Solenoid
- EM calorimeter
- Hadron calorimeter
- Muon system

Interaction point

Top Mass Measurements at the Tevatron