Top and W mass measurement at the Tevatron

Bob Hirosky
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for the CDF and D0 Collaborations

Moriond QCD 2016

\[ \sin^2 \theta_W \]
Top and W mass at the Tevatron

- Direct and indirect mass measurements
- Status and recent results from the 1.96 TeV pp program
Detailed check of consistency of the SM

Precision tests of EW sector

<= famous “triple point” plot of EW observables
Full constraint of SM

With an improved world average around 10 MeV dominated by the Tevatron
=> increasingly strong indirect tests for compatibility of SM observables, eg \( m_H \)

Significant anomaly could be detected with improved precision on \( m_W \), if central value drifts apart from EW fit.
Consistency of the SM/Fate of the Universe

Precise measure of top mass also a strong driver in consistency tests of SM, interesting question of vacuum stability

Phase diagram of the universe

Degrassi et al.

Higgs mass $M_h$ in GeV

$M_t$

$\Delta \chi^2$

Bob Hirosky, UNIVERSITY of VIRGINIA

Moriond QCD, 2016
Top production and decay signatures

- Tevatron and LHC: Largely complimentary production mode
- Very interesting for a variety of properties studies.
  (See talk by Dave Toback)

Well known decay signatures

- Exploit high mass, heavy flavor jets, isolated high \( p_T \) leptons for effective event ID

\[ \text{Top decay:} \]

- \( \sim 100\% \) with 2 valence quarks: \( v, q \)
- \( W^+ \rightarrow l^+ \bar{q}' \)

Top Pair Decay Channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>electron+jets</th>
<th>muon+jets</th>
<th>tau+jets</th>
<th>all-hadronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} )</td>
<td>( e^+ \mu^- )</td>
<td>( \mu^+ \tau^- )</td>
<td>( \tau^+ \bar{\nu} )</td>
<td>( t\bar{t} )</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>( e^+ \mu^- )</td>
<td>( \mu^+ \tau^- )</td>
<td>( \tau^+ \bar{\nu} )</td>
<td>( t\bar{t} )</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>( e^+ \mu^- )</td>
<td>( \mu^+ \tau^- )</td>
<td>( \tau^+ \bar{\nu} )</td>
<td>( t\bar{t} )</td>
</tr>
</tbody>
</table>

Dilepton (e/\( \mu \))

- 6%

\( e/\mu + \text{jets} \)

- 34%
**Template methods**
- Use variable sensitive to top mass (e.g. $m_t^{\text{reco}}$ from visible decay products)
- Maximum likelihood fit to mass templates

**Matrix element methods**
- Evaluate event probabilities $P(\text{signal})$ based on full event kinematics
- ~maximal use of event information

$$P_{t\bar{t}} = \frac{1}{\sigma_{t\bar{t}}(m_t)} \sum_j \sum_p \int dq_1 dq_2 \frac{d\sigma(p \bar{p} \rightarrow t \bar{t} \rightarrow y)}{dy} \cdot f(q_1) \cdot f(q_2) \cdot W(x; y) \cdot dy$$
- Mass extracted from global likelihood WRT input $m_t$

**Indirect methods**
- eg Pole mass from cross section measurement

$\Rightarrow$ Constrain JES insitu w/ hadronic W decays
Top quark mass in dileptons: neutrino weighting

\[ t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow b\bar{b}\ell^+\ell^-\nu\bar{\nu}; \ell = (e, \mu) \]

**Neutrino weighting method:**
- Integrate over phase space \((\eta_{\nu_1}, \eta_{\nu_2})\) for \(m_t^{\text{hypotheses}}\) and jet-lepton assignments
- Multiple kinematic reconstruction w/ weights \((\omega)\) for solutions based on calculated and observed MET
- Characterize events by moments of the distribution: \(\mu(\omega)\) and \(\sigma(\omega)\)

Jet energy correction factor derived from \(l+jets\) analysis (kJES) reduces JES uncertainty \(\sim 4x\)

Multiply likelihoods from all events for combined \(L(m_{top}^{MC})\)
Top quark mass in dileptons: neutrino weighting

- Reconstruction method optimized to minimize the expected statistical uncertainty
- Maximum likelihood fit to mass templates for S,B models

Most precise dilepton channel measurement at the Tevatron!

Main systematic uncertainties: JES and higher order effects

Achieve systematic uncertainty of 0.49% => smallest of all dilepton measurements.

\[ m_t = 173.32 \pm 1.36 \text{ (stat)} \pm 0.85 \text{ (syst)} \text{ GeV} \]

\[ \frac{\delta m_t}{m_t} = 0.93\% \]

Top quark mass in dileptons: matrix element

The matrix element approach is used to extract the most precise top quark mass measurement at the Tevatron in l+jets final state, extended to numerous other analyses in top physics and beyond.

Probability for events in data determined from S and B models using measured parameters $x$, eg components of 4-vectors of final state particles

$$P(x, f_{t\bar{t}}, m_t) = f_{t\bar{t}} \cdot P_{t\bar{t}}(x, m_t) + (1 - f_{t\bar{t}}) \cdot P_{bkg}(x)$$

- Sufficient to use dominant matrix elements $qq\bar{q}$ for signal production and $Z+\text{jets}$ background
- Minimize likelihood function wrt signal fraction ($f$) and $m_t$
- Improve JES uncertainty by applying calibration scale factor $k_{\text{JES}}$ measured in l+jets using jets associated with the W boson decay
Top quark mass in dileptons: matrix element

High purity (~90%) channel

Expected and observed events following selections

<table>
<thead>
<tr>
<th>Channel</th>
<th>Z/Γ*</th>
<th>Diboson</th>
<th>Instrumental</th>
<th>tt</th>
<th>Total</th>
<th>Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>13.0±1.7</td>
<td>3.7±0.8</td>
<td>16.4±4.0</td>
<td>260.6±22.5</td>
<td>293.8±23.5</td>
<td>346</td>
</tr>
<tr>
<td>ee</td>
<td>13.8±2.1</td>
<td>1.9±0.4</td>
<td>1.8±0.2</td>
<td>88.0±9.1</td>
<td>105.5±10.3</td>
<td>104</td>
</tr>
<tr>
<td>μμ</td>
<td>10.6±1.3</td>
<td>1.7±0.4</td>
<td>0</td>
<td>76.0±6.2</td>
<td>88.3±6.7</td>
<td>92</td>
</tr>
<tr>
<td>ℓℓ</td>
<td>37.4±5.1</td>
<td>7.3±1.6</td>
<td>18.2±4.0</td>
<td>424.6±37.8</td>
<td>487.6±40.5</td>
<td>545</td>
</tr>
</tbody>
</table>

<= Jet p_T distribution after kJES correction and data/prediction ratio (combined ee, eμ, μμ channels)

Method is calibrated for biases in measured m_t and statistical uncertainty by repeating the measurement using generated data-like ensembles =>
Top quark mass in dileptons: matrix element

$\leq$ NLL values calculated for the observed data as a function of generated $m_{top}$ (before calibration)

$m_t$ (post calibration) with statistical uncertainties

<table>
<thead>
<tr>
<th></th>
<th>$ee$</th>
<th>$e\mu$</th>
<th>$\mu\mu$</th>
<th>$\ell\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>176.9 ± 4.6 GeV</td>
<td>172.2 ± 2.0 GeV</td>
<td>176.0 ± 4.8 GeV</td>
<td>173.9 ± 1.5 GeV</td>
</tr>
</tbody>
</table>

**Dominant systematic uncertainties**

- Hadronization & UE +0.31
- b-jet modelling +0.21
- PDF uncertainty ±0.20
- Uncertainty on kJES ±0.46
- Flavor dependent jet response ±0.30
- b-tagging efficiency ±0.28

$m_t = 173.9 \pm 1.5 \text{ (stat)} \pm 0.9 \text{ (syst)} \text{ GeV}$

$\delta m_t/m_t = 1\%$

Combination w/ $\nu$-weighting analysis in progress

D0 Note 6483–CONF
Top quark pole mass

Direct measures shown based on $m_t^{\text{MC}} = m_t^{\text{pole}}$ (but close $\Delta \sim 1\text{GeV}$)
Can not be used directly for precise NLO / NNLO theoretical predictions

$m_t^{\text{pole}}$ can be extracted from inclusive cross-section measurement

Well defined mass parameter in QFT

Use l+jets and dilepton channel data

MVA method, simultaneous template fit for XS

(see talk by D. Toback)
Top quark pole mass

$m_t^{\text{pole}}$ determined using experimental dependence of $\sigma_{tt}$ on $m_t$.

<table>
<thead>
<tr>
<th>Top quark mass [GeV]</th>
<th>Cross section $\sigma(t\bar{t})$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>10.53 ± 0.17 (stat.) +0.78 (syst.)</td>
</tr>
<tr>
<td>160</td>
<td>9.24 ± 0.16 (stat.) +0.74 (syst.)</td>
</tr>
<tr>
<td>165</td>
<td>8.07 ± 0.14 (stat.) +0.65 (syst.)</td>
</tr>
<tr>
<td>170</td>
<td>8.28 ± 0.14 (stat.) +0.57 (syst.)</td>
</tr>
<tr>
<td>172.5</td>
<td>7.73 ± 0.13 (stat.) +0.55 (syst.)</td>
</tr>
<tr>
<td>175</td>
<td>7.80 ± 0.13 (stat.) +0.51 (syst.)</td>
</tr>
<tr>
<td>180</td>
<td>7.42 ± 0.13 (stat.) +0.50 (syst.)</td>
</tr>
<tr>
<td>185</td>
<td>6.92 ± 0.12 (stat.) +0.45 (syst.)</td>
</tr>
<tr>
<td>190</td>
<td>6.85 ± 0.12 (stat.) +0.43 (syst.)</td>
</tr>
</tbody>
</table>

Most probable $m_t$ and uncertainty calculated via joint likelihood of data, NNLO pQCD, and related uncertainties.

In agreement with world average MC mass of 173.34±0.76 GeV

Most precise determination of $m_t^{\text{pole}}$ at the Tevatron.

$m_t = 169.5^{+3.3}_{-3.4} (\text{tot.})$ GeV

D0 Preliminary
(Indirect) measurement of $W$ mass

$m_W$ can be determined indirectly via the relation

$$\sin^2 \theta_W^{\text{on-shell}} = 1 - \frac{M_W^2}{M_Z^2}$$

$\pm 0.00040$ error in $\sin^2 \theta_W$ is equiv. to $\pm 20$ MeV error in $M_W$ (indirect)

Both $\sin^2 \theta_W^{\text{on-shell}}$ and $\sin^2 \theta_W^{\text{leptonic}}$ ($M_Z$) can be extracted from Drell-Yan forward-backward asymmetry (Afb) if we include EW radiative corrections. $M_W^{\text{indirect}}$ can be extracted from $\sin^2 \theta_W^{\text{on-shell}}$

If the SM is correct, then both direct and indirect measurements of $m_W$ should agree. Deviations may imply the presence of new physics.
$\sin^2 \theta_W$ can be measured precisely at a hadron collider

MC carefully corrected to describe data:

- Smearing of electron energy
- Efficiency corrections in $p_T(e)$, $\eta(e)$
- $L_{\text{inst}}$ and $Z_{\text{PV}}$ reweighting to match data
- Higher order effects: NNLO $Z$ $p_T$ and $y$ to match RESBOS

Produce 2D templates of $m_{ee}$ and $\cos \theta^*$ by reweighing default MC as a function of $\sin^2 \theta_{\text{eff}}$

Extract $\sin^2 \theta_{\text{eff}}$ by fitting raw $A_{FB}$ to templates with different $\sin^2 \theta_{\text{eff}}$ values

$$\sin^2 \theta_{\text{eff}} = 0.23138 \pm 0.00043 (\text{stat}) \pm 0.00008 (\text{syst}) \pm 0.00017 (\text{NNPDF}2.3 \text{ PDFs})$$

O(0.2%) measure!

CDF: new $Z \rightarrow ee$ analysis including full unfolding for resolution and FSR

- Full ZFITTER EW radiative corrections
- Precise lepton momentum/energy scale for e/$\mu$
- Event weighting method to reduce systematic errors in acceptance and efficiencies
- Use Drell-Yan forward-backward asymmetry to constrain parton distribution functions

Example $\sin^2\theta_W$ template scan

$A_{FB}$ template:
- Powheg-Box
- NLO+NNPDF3.0

CDF $ee$ & $\mu\mu$

$\sin^2\theta_{eff} = 0.23221 \pm 0.00046$ (total)

arXiv:1512.08256
CDF ee & μμ 9 fb^{-1} indirect $M_W$ measurement

Indirect Measurements
- LEP-1 and SLD ($m_t$) 80.363±0.020
- NuTeV 80.135±0.085
- CDF $\mu\mu$ 9 fb^{-1} 80.365±0.047
- CDF ee 9 fb^{-1} 80.313±0.027
- CDF $ee+\mu\mu$ 9 fb^{-1} 80.328±0.024

Direct Measurement
- TeV and LEP-2 Direct Measurement 80.385±0.015

PDG 2014
- $m_t$ (GeV)
- $m_W$ (GeV)

SM

Next: CDF-D0 combination (in future)

A. Bodek, Moriond EW 2016
Moriond QCD, 2016
Conclusion

Tevatron finalizing measurements with full data set
• Many top mass measurements updated since World combination (Mar '14)
• Increased precision of Tevatron combination, more optimized analyses
• Updated high precision weak mixing angle measurements

Currently the Tevatron direct (L= 2.2–5.3 fb^{-1}) and indirect (L=9.4 fb^{-1}) measurements of m_W have similar errors. (~ 20 MeV per experiment)

Tevatron Run II Legacy measurements of sin2θ_w and m_W^{indirect} are in agreement with SM predictions from m_H and m_t

Direct measurements of m_W with full Tevatron data in progress

Further precision in Tevatron and world combinations will tighten focus on SM physics and beyond
Additional slides
Indirect measurement of $W$ mass

→ using the measurement of weak mixing angle

CDF note 11178

In all orders of perturbation theory:

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

on-shell particle masses
Top mass – world combination

• Using analytic BLUE method
  – determines the weights, which are used in a linear combination of the inputs
  – minimize total uncertainty

\[ M_t = 173.34 \pm 0.76 \text{ GeV} \]
\[ \delta m_t / m_t = 0.44\% \]
\[ \chi^2 = 4.3/10 \text{ NDF} \text{ (93\%)} \]

arXiv:1403.4427 [hep-ex]

P. Bartoš
La Thuile 2016, March 6
**Top mass – world combination**

**Tevatron+LHC $m_{top}$ combination - March 2014, $L_{int} = 3.5 \text{ fb}^{-1} - 8.7 \text{ fb}^{-1}$**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$m_{top}$ [GeV]</th>
<th>стат.</th>
<th>JES</th>
<th>syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF RunII, l+jets</td>
<td>172.85 ± 1.12</td>
<td>0.52 ± 0.49</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>CDF RunII, di-lepton</td>
<td>170.28 ± 3.69</td>
<td>1.95</td>
<td>± 3.13</td>
<td></td>
</tr>
<tr>
<td>CDF RunII, all jets</td>
<td>172.47 ± 2.01</td>
<td>1.43</td>
<td>± 0.95 ± 1.04</td>
<td></td>
</tr>
<tr>
<td>CDF RunII, $E_{T}^{miss}$+jets</td>
<td>173.93 ± 1.85</td>
<td>1.26</td>
<td>± 1.05 ± 0.86</td>
<td></td>
</tr>
<tr>
<td>D0 RunII, l+jets</td>
<td>174.94 ± 1.50</td>
<td>0.83</td>
<td>± 0.47 ± 1.16</td>
<td></td>
</tr>
<tr>
<td>D0 RunII, di-lepton</td>
<td>174.00 ± 2.79</td>
<td>2.36</td>
<td>± 0.55 ± 1.38</td>
<td></td>
</tr>
<tr>
<td>ATLAS 2011, l+jets</td>
<td>172.31 ± 1.55</td>
<td>0.23</td>
<td>± 0.72 ± 1.35</td>
<td></td>
</tr>
<tr>
<td>ATLAS 2011, di-lepton</td>
<td>173.09 ± 1.63</td>
<td>0.64</td>
<td>± 1.50</td>
<td></td>
</tr>
<tr>
<td>CMS 2011, l+jets</td>
<td>173.49 ± 1.06</td>
<td>0.27</td>
<td>± 0.33 ± 0.97</td>
<td></td>
</tr>
<tr>
<td>CMS 2011, di-lepton</td>
<td>172.50 ± 1.52</td>
<td>0.43</td>
<td>± 1.46</td>
<td></td>
</tr>
<tr>
<td>CMS 2011, all jets</td>
<td>173.49 ± 1.41</td>
<td>0.69</td>
<td>± 1.23</td>
<td></td>
</tr>
</tbody>
</table>

**World comb. 2014**

- $\chi^2$/ndf = 4.3/10
- $\chi^2$ prob = 93%

- $m_{top} = 173.34 \pm 0.76$ (0.27 ± 0.24 ± 0.67)

**Previous Comb.**

- Tevatron March 2013 (Run I+II)
- LHC September 2013

**UPDATE after combination**

<table>
<thead>
<tr>
<th>$m_{top}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>173.20 ± 0.87</td>
</tr>
<tr>
<td>(0.51 ± 0.36 ± 0.61)</td>
</tr>
</tbody>
</table>

**arXiv:1403.4427 [hep-ex]**

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P. Bartoš, LaThuile 2016
Moriond QCD, 2016
Top mass – Tevatron combination

- BLUE method used
- Includes Run I results
- 3 measurements updated after world combination: D0 I+jets, CDF dilepton & all-jets

<table>
<thead>
<tr>
<th>Tevatron combined values (GeV/c²)</th>
<th>174.34</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ light-jet calibration (iJES)</td>
<td>0.31</td>
</tr>
<tr>
<td>Response to b/q/g jets (aJES)</td>
<td>0.10</td>
</tr>
<tr>
<td>Model for b jets (bJES)</td>
<td>0.10</td>
</tr>
<tr>
<td>Out-of-cone correction (cJES)</td>
<td>0.02</td>
</tr>
<tr>
<td>Light-jet response (1) (rJES)</td>
<td>0.05</td>
</tr>
<tr>
<td>Light-jet response (2) (dJES)</td>
<td>0.13</td>
</tr>
<tr>
<td>Lepton modeling (LepPt)</td>
<td>0.07</td>
</tr>
<tr>
<td>Signal modeling (Signal)</td>
<td>0.34</td>
</tr>
<tr>
<td>Jet modeling (DetMod)</td>
<td>0.03</td>
</tr>
<tr>
<td>b-tag modeling (b-tag)</td>
<td>0.07</td>
</tr>
<tr>
<td>Background from theory (BGMC)</td>
<td>0.04</td>
</tr>
<tr>
<td>Background based on data (BGData)</td>
<td>0.08</td>
</tr>
<tr>
<td>Calibration method (Method)</td>
<td>0.07</td>
</tr>
<tr>
<td>Offset (UN/MI)</td>
<td>0.00</td>
</tr>
<tr>
<td>Multiple interactions model (MHI)</td>
<td>0.06</td>
</tr>
<tr>
<td>Systematic uncertainty (syst)</td>
<td>0.52</td>
</tr>
<tr>
<td>Statistical uncertainty (stat)</td>
<td>0.37</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.64</td>
</tr>
</tbody>
</table>

July 2014 preliminary

Red box: positive weights
Grey box: absolute value of negative weights


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Moriond QCD, 2016
Top mass – Tevatron combination

Mass of the Top Quark

<table>
<thead>
<tr>
<th>July 2014</th>
<th>(* preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I dilepton</td>
<td>167.40 ± 11.41 (±10.30 ± 4.90)</td>
</tr>
<tr>
<td>DØ-I dilepton</td>
<td>168.40 ± 12.82 (±12.30 ± 3.60)</td>
</tr>
<tr>
<td>CDF-II dilepton *</td>
<td>170.80 ± 3.26 (±1.83 ± 2.69)</td>
</tr>
<tr>
<td>DØ-II dilepton</td>
<td>174.00 ± 2.80 (±2.36 ± 1.49)</td>
</tr>
<tr>
<td>CDF-I lepton+jets</td>
<td>176.10 ± 7.36 (±5.10 ± 5.30)</td>
</tr>
<tr>
<td>DØ-I lepton+jets</td>
<td>180.10 ± 5.31 (±3.90 ± 3.60)</td>
</tr>
<tr>
<td>CDF-II lepton+jets</td>
<td>172.85 ± 1.12 (±0.52 ± 0.98)</td>
</tr>
<tr>
<td>DØ-II lepton+jets</td>
<td>174.98 ± 0.76 (±0.41 ± 0.63)</td>
</tr>
<tr>
<td>CDF-I alljets</td>
<td>186.00 ± 11.51 (±10.00 ± 5.70)</td>
</tr>
<tr>
<td>CDF-II alljets *</td>
<td>175.07 ± 1.95 (±1.19 ± 1.55)</td>
</tr>
<tr>
<td>CDF-II track</td>
<td>166.90 ± 9.43 (±9.00 ± 2.82)</td>
</tr>
<tr>
<td>CDF-II MET+Jets</td>
<td>173.93 ± 1.85 (±1.26 ± 1.36)</td>
</tr>
<tr>
<td>Tevatron combination *</td>
<td>174.34 ± 0.64 (±0.37 ± 0.52)</td>
</tr>
</tbody>
</table>

\( M_t = 174.34 ± 0.64 \text{ GeV} \)
\( \frac{\delta m}{m} = 0.37\% \)
\( \chi^2 = 10.8/11 \text{ NDF (46\%)} \)


after combination

March 6-12

P. Bartoš, LaThuile 2016
The Tevatron: Run 2

10 year program of data collection, world's highest energy pp collisions

~ 10 fb⁻¹ events recorded / per experiment

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