Top Quark Mass Measurements at the Tevatron

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Outline

1. Top quark and its mass
2. Methods of measurement
3. Measurements
   - ℓ+jets final state
   - $\not\!\!E_T$ +jets final state
4. Tevatron combination
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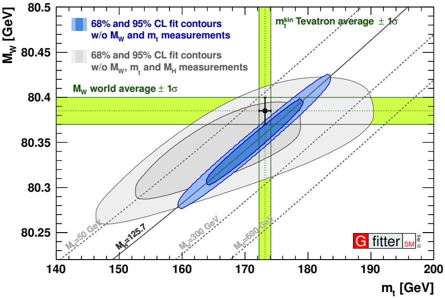
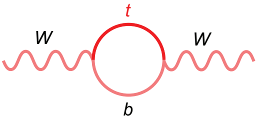
The top quark and its mass

- top quark is the heaviest among the observed particles
- it can be measured directly: it decays before hadronizing
- its mass, m_t, is a free parameter of Standard Model:
  - present in loop corrections of W mass
  - with t, W and H masses, the SM predictions are severely tested
- a precise measurement helps understanding our models



Global fit of measurements in the SM [1]

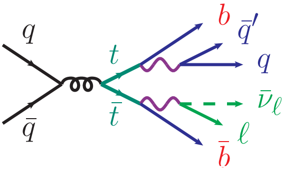


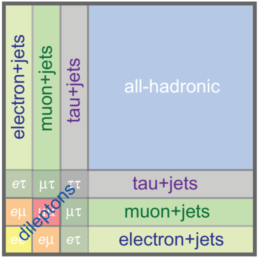
Experimental signatures

Top quarks are produced by strong interaction in $t\bar{t}$ pairs.

Each decays into a quark and a *W* boson:

- final state determined by *W* decays:
  - "di-lepton" extremely pure, low rate, no fully reconstructed *t*
  - "ℓ+jets" compromise: good purity, one fully reconstructed *t*
  - "all-jet" large background, two fully reconstructed *t*
- the quark is almost always a *b* quark:
  - jets from *b* contain long-lived *B* hadrons
  - their features can often be identified in the jet
  - ⇒ we call such jets "*b*-tagged"

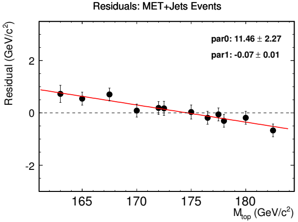




Measurement method

The measurements of top mass goes through some common steps:

1. assign a likelihood for each event, function of the top mass: $L_i(m_t; \ldots)$
2. maximize a global likelihood $L(m_t; \ldots) = \prod_{i \in \text{events}} L_i(m_t; \ldots)$, including all the events, to extract the m_t estimator
3. calibrate to remove any bias of the method



Calibration curve of m_t from CDF measurement from 8.7 fb^{-1} in $\not{E}_T$ +jets

- our analyses are calibrated on Monte Carlo simulation

⇒ we measure m_t with the definition implemented in MC!

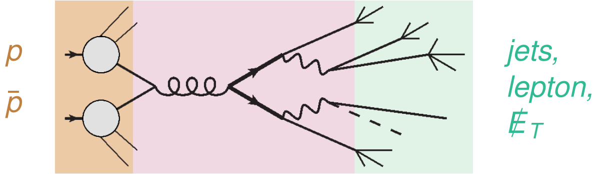
- the precision of the experimental measurements helps the *interpretation* of this parameter *(cfr. PRD **80**, 071102 (2009))*

Methods: Matrix Element

Matrix Element method exploits the full topology of the event:

$$P(x, m_t) = \frac{1}{\sigma(m_t)} \int \sum_{\text{flavours}} f(q_1)\, f(q_2)\, \sigma(y, m_t)\, \mathcal{W}(x, y)\ dq_1\, dq_2\ dy$$

scattering matrix element (in σ) for a final-state parton configuration "y" (including 4-momenta of all the 6 final state particles)



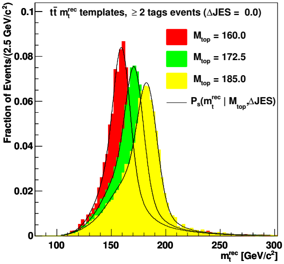
probability $f(q_{1/2})$ of having a specific initial state (*Parton Distribution Functions*)

probability $\mathcal{W}$ of reconstructing the scattering final state "y" as our measured jets/lepton objects "x" (*Transfer Functions*)

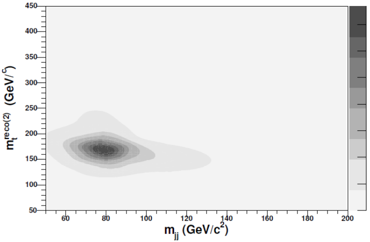
Methods: templates

Templates method interprets the distribution of one or more observables sensitive to m_t as probability densities:

- distributions are extracted from full detector simulation
- correlations between observables *can* be included
- up to three observables used



m_t template (CDF measurement from 5.8 fb^{-1} in all-hadronic final state)



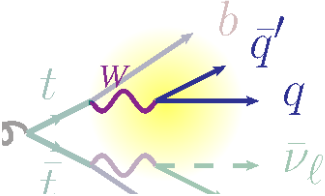
m_t vs. m_{jj} template (m_t=171.5 GeV/c^2) from CDF measurement from 8.7 fb^{-1} in ℓ+jets

in situ Jet Energy Scale Calibration

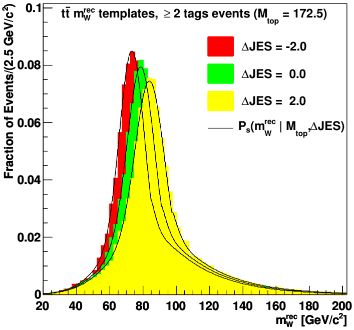
- in some final states, *W* boson can be *fully reconstructed*

⇒ constrain a m_W estimator with the known W mass

- “nuisance parameter” Δ_{JES} is measured, describing an additional global scale of jet energy



$t\bar{t}$ diagram with $W \to q\bar{q}$



m_{jj} template (CDF measurement from 5.8 fb^{-1} in all-hadronic final state, m_t=172.5 GeV/c^2)

Existing measurements

Four experiments measure m_t; most precise results to date:

CDF (Tevatron)

ℓ+jets, Matrix Element on 5.6 fb^{-1}:
173.0 ± 0.9 *(stat.+JES)* $\pm\, 0.9$ *(syst.)*
(rel: 0.7%) [2] *(update in this talk!)*

DØ (Tevatron)

ℓ+jets, Matrix Element on 3.6 fb^{-1}:
174.9 ± 1.1 *(stat.+JES)* $\pm\, 1.0$ *(syst.)*
(rel: 0.85%) [3]

Tevatron: CDF and DØ combination (July 2012)

From many channels, up to 5.8 fb^{-1} *(update in this talk!)*:

m_t=173.18 $\pm$ 0.56 *(stat.)* $\pm$ 0.75 *(syst)* GeV/c^2 (rel: 0.54%) [4]

LHC combination (ATLAS and CMS)

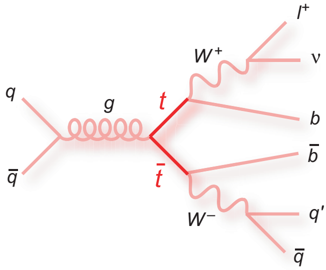
m_t=173.3 $\pm$ 0.5 *(stat.)* $\pm$ 1.3 *(syst)* GeV/c^2 (rel: 0.8%) [5]

CDF measurement: ℓ+jets [PRL **109**, 152003 (2012)]

The event selection:

- one isolated electron or muon
- four or more jets
- sample split according to the number of identified *b*-jets

⇒ up to 24 jet-to-quark assignment combinations

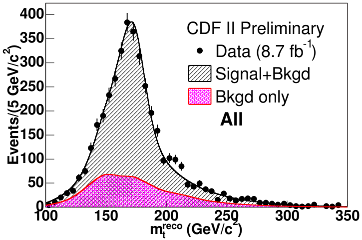


Improvements on the existing 5.6 fb^{-1} measurement:

- full CDF dataset: 8.7 fb^{-1}
- Jet Energy Scale improved by an additional calibration based on multivariate analysis
- addition of the data sample with no identified *b*-jets

Templates are built with three observables (*including correlations*):

- two top mass estimators, m_t^{reco} and $m_t^{reco(2)}$, from the two most $t\bar{t}$-like combinations
- m_{jj}, mass of the two non-b-tagged jets which is closest to M_W

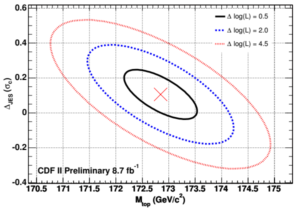


CDF 8.7 fb^{-1} top mass from ℓ+jets:

172.85 ± 0.71 *(stat.+JES)* ± 0.85 *(syst.)* GeV/c^2
$= 172.85 \pm 1.11$ GeV/c^2 *(rel. 0.63%)*

Leading uncertainties [GeV/c^2]:

signal model	0.56	background shape	0.20
residual JES	0.52	b-JES	0.18



The final state:

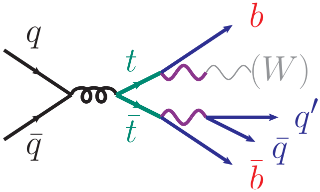
- four to six jets
- large transverse momentum imbalance ($\not\!\!E_T$)

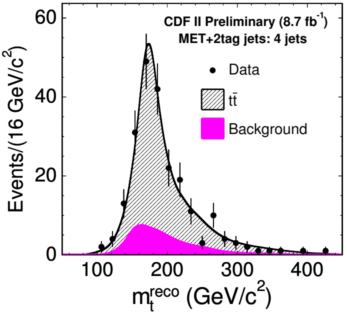
Main differences w.r.t. ℓ+jets analyses:

- templates method adapted for missing *W*
- at least one *b*-tagged jet is required
- a multivariate discriminant enhances the purity of the sample (to S:B = 2:1)

CDF 8.7 fb^{-1} top mass from $\not\!\!E_T$ +jets:

173.9 ± 1.6 *(stat.+JES)* ± 0.9 *(syst.)* GeV/c^2
= 173.9 ± 1.9 GeV/c^2 *(rel. 1.1%)*





Combination of mass measurements

A joint CDF and DØ working group performs the combination of top quark measurements: mass, $t\bar{t}$ production cross section and properties.

- using Best Linear Unbiased Estimator
- requires the knowledge of the correlation of uncertainties between measurements

⇒ a lot of care must be taken in defining the systematic uncertainties

- systematic distributions are assumed (symmetric) gaussian

In selecting the measurements among the ≈ 50 that the collaborations published, the focus is on precision and independence.

Measurements included in the combination

12 results from the two experiments are combined:

ℓ+jets

- 0.1 fb^{-1}
- 0.1 fb^{-1}, matrix element
- 8.7 fb^{-1}, *templates*
- 3.6 fb^{-1}, matrix element
- 1.9 fb^{-1}, decay length

$\ell\ell$+jets

- 0.1 fb^{-1}
- 0.1 fb^{-1}, templates
- 5.6 fb^{-1}, templates
- 5.3 fb^{-1}, templates

all jets

- 0.1 fb^{-1}
- 5.8 fb^{-1}, templates
- 8.7 fb^{-1}, *with* $\not\!\!E_T$

Measurements included in the combination

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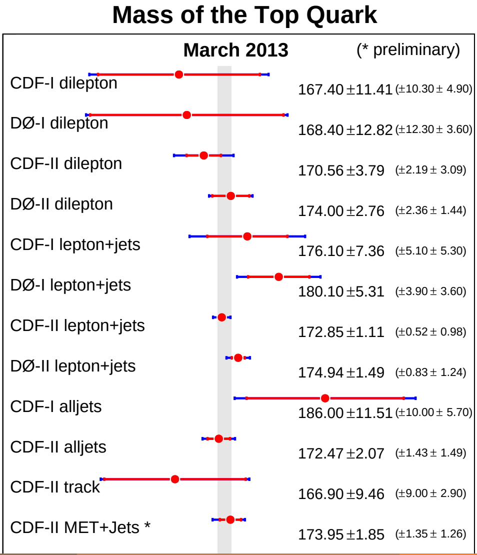


March 2013 combination [TeVcomb]

- uncertainties are split in 14 categories:
  - jet energy scale (7)
  - signal modelling
  - background modelling (2)
  - modelling of reconstructed objects (2)
  - modelling of additional $p\bar{p}$ interactions
  - calibration method
- their definitions are chosen in such a way that they are either uncorrelated or fully correlated between measurements

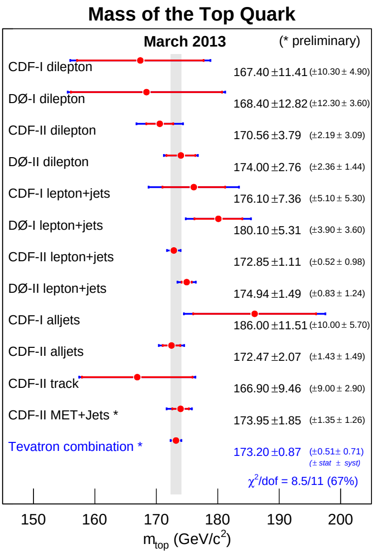
Mass measurements from Tevatron: March 2013 combination

$$m_t = 173.20 \pm 0.51\,(stat.) \pm 0.71\,(syst.)\ \mathrm{GeV}/c^2$$
$$= 173.20 \pm 0.87\ \mathrm{GeV}/c^2 \qquad (rel.\ 0.50\%)$$

Dominant uncertainties: Jet Energy Scale and Signal Modelling

Summary and outlook

- precision measurement of the mass of top quark is still important
  - today it is measured with a precision of 0.50%!
- first CDF measurements with the complete dataset
- current challenge: reducing systematic uncertainties
- measurements are all consistent



References to the measurements described in this talk

[CDFℓ+jets] The CDF Collaboration,
"Precision Top-quark Mass Measurement at CDF",
PRL **109**, 152003 (2012), [arxiv:1207.6758 [hep-ex]]

[CDF$\not\!\!E_T$ +jets] The CDF Collaboration,
"A Measurement of Top Quark Mass Using MET + Jets Events With Full CDF Data Set 8.7 fb^{-1}",
CDF note 10810, 05/16/2012

[TeVcomb] The CDF Collaboration,
"Combination of CDF and DØ results on the mass of the top quark using up to 8.7 fb^{-1} of $p\bar{p}$ collisions",
CDF note 10976, DØ note 6381, March 2013

Other references

[1] from the GFitter collaboration,
Standard Model plots on September 2012
(http://gfitter.desy.de/Standard_Model)

[2] The CDF Collaboration,
"Top Quark Mass Measurement in the lepton+jets Channel Using a Matrix Element Method and *in situ* Jet Energy Calibration",
PRL **105**, 252001 (2010) [arxiv:1010.4582 [hep-ex]]

[3] The DØ Collaboration,
"Precise measurement of the top-quark mass from lepton+jets events at D0",
PRD **84**, 032004 (2011) [arxiv:1105.6287 [hep-ex]]

[4] The CDF and DØ Collaborations,
"Combination of the top-quark mass measurements from the Tevatron collider",
PRD **86**, 092003 (2012) [arxiv:1207.1069 (v4) [hep-ex]]

[5] The ATLAS and CMS Collaborations,
"Combination of ATLAS and CMS results on the mass of the top quark using up to 4.9 fb^{-1} of data",
ATLAS-CONF-2012-095, CMS-PAS-TOP-12-001, July 2012

CDF ℓ+jets measurement: combinations and χ^2

The four jets can be combined in the W and t in different ways; for each of them, the quantity:

$$\begin{aligned}\chi^2\left(m_t^{reco}\right) &= \sum_{jets}\frac{\left(p_T^{i,\text{fit}} - p_T^{i,\text{meas}}\right)^2}{\sigma_i^2} + \sum_{k=x,y}\frac{\left(U_k^{\text{fit}} - U_k^{\text{meas}}\right)^2}{\sigma_k^2} \\ &+ \frac{\left(M_{jj} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{\ell\nu} - M_W\right)^2}{\Gamma_W^2} \\ &+ \frac{\left(M_{bjj} - m_t^{reco}\right)^2}{\Gamma_t^2} + \frac{\left(M_{b\ell\nu} - m_t^{reco}\right)^2}{\Gamma_t^2}\end{aligned}$$

is minimized, where σ's and Γ's are experimental resolutions and theoretical widths, and $M_W = 80.4\ \text{GeV}/c^2$.

- jet momentum and $\not{E}_T$ are allowed to float within their resolution
- the jet energies are constrained by the known W mass
- the top mass estimator m_t^{reco} is taken from the minimization

CDF $\not{E}_T$ +jets measurement: combinations and χ^2

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$$
\begin{aligned}
\chi^2(m_t^{reco}) &= \sum_{jets} \frac{\left(p_T^{i,\mathrm{fit}} - p_T^{i,\mathrm{meas}}\right)^2}{\sigma_i^2} + \sum_{k=x,y} \frac{\left(U_k^{\mathrm{fit}} - U_k^{\mathrm{meas}}\right)^2}{\sigma_k^2} \\
&+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} \\
&+ \frac{(M_{bjj} - m_t^{reco})^2}{\Gamma_t^2} + \frac{\left(M_{b,\mathrm{missing}} - m_t^{reco}\right)^2}{\Gamma_t^2}
\end{aligned}
$$

is minimized, where σ's and Γ's are experimental resolutions and theoretical widths, and $M_W = 80.4\ \mathrm{GeV}/c^2$.

- jet momenta are allowed to float within their resolution
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Comparison of Tevatron and LHC combinations

Uncertainty [GeV/c^2]	Tevatron July 2012	Tevatron **March 2013**	LHC June 2012
Measured m_t	173.18	**173.20**	173.34
Statistical	0.56	**0.51**	0.47
Systematic	0.75	**0.71**	1.33
Total	0.94	**0.87**	1.40

Systematic uncertainties of combination

Uncertainty name [GeV/c^2]	Tevatron July 2012	Tevatron **March 2013**	LHC June 2012	CDF ℓ+jets
In situ light-jet calibration	0.39	**0.36**	0.38	0.49
Response to *b*/*q*/*g* jets	0.09	**0.09**	n/a	0.09
Model for *b*-jets	0.15	**0.11**	0.68	0.16
Out-of-cone correction	0.05	**0.01**	n/a	0.21
Light-jet response (2)	0.20	**0.15**	0.07	0.07
Light-jet response (1)	0.12	**0.16**	0.06	0.48
Lepton modelling	0.10	**0.05**	0.01	0.03
Signal modelling	0.51	**0.52**	0.88	0.61
Jet modelling	0.10	**0.08**	0.19	0.00
Offset	0.00	**0.00**	0.47	n/a
Background from theory	0.14	**0.06**	0.01	0.12
Background based on data	0.11	**0.13**	0.16	0.16
Calibration method	0.09	**0.06**	0.13	0.00
Multiple interactions model	0.08	**0.07**	0.25	0.07

Systematic uncertainties of combination (II)

Differences between LHC and Tevatron categories:

Response to $b/q/g$ jets in LHC is shared by the b-jet model and the light-jet response (2)

Out-of-cone correction in LHC is included in the light-jet response (2)

Light-jet response (2) from uncertainties on the calibration samples

Light-jet response (1) remaining JES uncertainties (except 2)

Offset for Tevatron, this is RunI DØ uncertainty only; in LHC is from the modelling of the pile-up events

Systematic uncertainties of CDF ℓ+jets measurement

	ℓ+jets	$\not\!\!E_T$ +jets
Measured value	172.85	173.9
Residual jet energy scale	0.52	0.4
Signal modelling	0.56	0.4
Higher-order corrections	0.09	
b-jet energy scale	0.18	0.2
b-tagging efficiency	0.03	
Initial and final state radiation	0.06	0.3
Parton distribution functions	0.08	0.2
Gluon fusion fraction	0.03	0.3
Lepton energy scale	0.03	
Background shape	0.20	0.2
Multiple hadron interaction	0.07	0.2
Colour reconnection	0.21	0.3
MC statistics	0.05	
Trigger simulation		0.1
Calibration		0.2
Total systematic	0.85	0.9
Total statistical	0.71	1.6