Top-quark mass measurements with alternative methods

top LHC–France 2015

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Introduction

"Classical" measurements:

directly inferring m_{top} from the top-quark decay products

- are dominated by systematic errors
  ↪ most of which are correlated across channels, methods, and experiments
- give the input MC top-quark mass parameter
  ↪ a properly defined short distance mass should enter the SM fits

"Alternative" measurements:

measuring kinematic or dynamic variables correlated to m_{top}

- measurements whose systematic uncertainties are as less as possible correlated to the latter ones

or

- analyses explicitly sensitive to the top-quark pole mass

arXiv:1403.4427

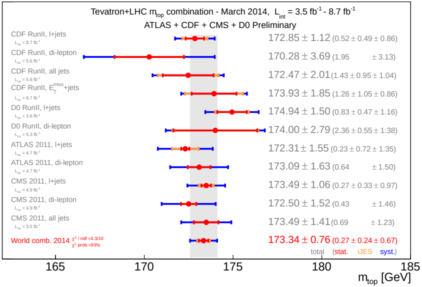


Figure 1: Input measurements and result of the world combination. The overall uncertainty is dominated by *in situ* JES and systematic uncertainties.

Outline

Using the invariant mass of the 2 lepton plus b-jet pairs

- Among $\sqrt{s} = 7$ TeV data (4.7 fb^{-1}), selecting dileptonic $t\bar{t}$ events (e^+e^-, $\mu^+\mu^-$, and $e^{\pm}\mu^{\mp}$) with ≥ 2 jets, of which exactly 2 are b-tagged
- For each event, computing $m_{\ell b}$ for the 2 top-quarks, considering the jet assignment leading to the lowest average mass
  $\hookrightarrow$ correct in 77% of the cases
- Performing a likelihood fit for Gaussian + Landau templates generated for 7 values of m_{top}^{MC} between 165 and 180 GeV/c^2

arXiv:1503.05427

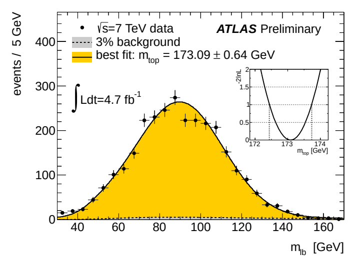


Figure 2: Fitted $m_{\ell b}$ distribution in data. The inset shows the -2 log likelihood profile as a function of the fitted top-quark mass.

$$m_{top} = 173.09 \pm 0.64\,(\text{stat.}) \pm 1.50\,(\text{syst.})\ \text{GeV/c}^2$$

Main systematic sources:
JES, bJES, and b-tagging efficiency

Using the invariant mass of a lepton plus b-jet pair

- Among $\sqrt{s} = 8$ TeV data (19.7 fb^{-1}), selecting $e^{\pm}\mu^{\mp}$ dileptonic $t\bar{t}$ events with ≥ 2 jets, of which at least 1 is b-tagged
- For each event, computing $m_{\ell b}$ for only 1 of the top-quarks: the b-jet of highest p_T is associated to one of the leptons, so that the lowest invariant mass is obtained
  $\hookrightarrow$ correct in 85% of the cases
- Top-quark mass derived by comparison (χ^2 minimization) of the experimentally observed yields in individual bins of the $m_{\ell b}$ distribution with the prediction for different values of m_{top}^{MC} between 166.5 and 178.5 GeV/c^2

CMS PAS TOP-14-014

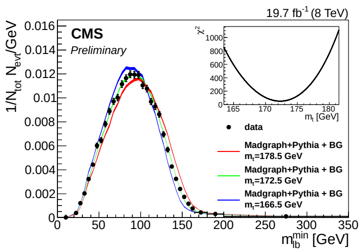


Figure 3: Normalized event yields for $t\bar{t}$ production, presented as a function of $m_{\ell b}$. The inset shows the χ^2 distribution as a function of the MC simulation parameter.

$$m_{top} = 172.3 \pm 1.3 \ \text{GeV}/c^2$$

Main systematic sources:
JES, bJES, and b-tagging efficiency

Single-top enhanced topologies

- Among $\sqrt{s} = 8$ TeV data (20.3 fb^{-1}), selecting single-top events with 1 lepton and 2 jets, of which 1 is b-tagged (t-channel)
  $\hookrightarrow$ color reconnection and Q^2 scale very different from the $t\bar{t}$ decays
- Defining signal and control regions to train a 3-layer feed-forward neural network with a preprocessing of 12 input variables.
  $\hookrightarrow$ a requirement on the neural-network based discriminant increases the proportion of t-channel events from 13% to 47%
- Performing a likelihood fit of the $m_{\ell b}$ distribution for Gaussian + Landau templates generated for 7 values of m_{top}^{MC} between 165 and 180 GeV/c^2

ATLAS CONF 2014-055

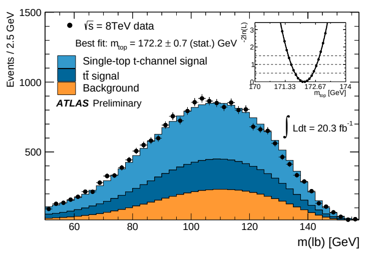


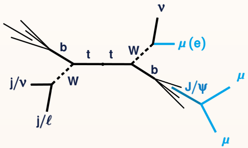
Figure 4: Fitted $m_{\ell b}$ distribution in data with the normalization and m_{top} being the best fit values. The inset show the -2 log likelihood profile as a function of the top-quark mass.

$$m_{top} = 172.2 \pm 0.7\,(\text{stat.}) \pm 2.0\,(\text{syst.})\ \text{GeV/c}^2$$

Main systematic uncertainties:
JES and hadronization

Leptonic final states with $b \to J/\psi + X \to \mu^+\mu^- + X$

- Using the correlation between the top-quark mass and the invariant mass of the $J/\psi + \ell$ combination $\to$ CERN/LHCC92-3 (1992) 90
- Systematic uncertainties mainly imputable to b-fragmentation, not impacted by jet-related sources or b-tagging
- Low branching ratio: $BR(t\bar{t} \to (W^+b)(W^-\bar{b}) \to (\bar{\ell}\nu_\ell J/\psi X)(qq'\bar{b})) \sim 0.55\%$
  Considering only $J/\psi \to \mu^+\mu^-$ and $\ell \in \{e, \mu\}$: $BR \sim 2.1 \cdot 10^{-4}$
  $\hookrightarrow$ 1st time this method is tried, with 8 TeV data



Analysis in progress at LPNHE by F. Derue

Analysis in progress at IPNL

Leptonic final states with $b \to J/\psi + X \to \mu^+\mu^- + X$

- Selecting events with 1(2) isolated lepton(s) (e or μ), 1 opposite-sign di-muon pair whose invariant mass is around the J/ψ one, and satisfying a jet criterion, among $\sqrt{s} = 8$ TeV data (19.8 fb^{-1})
- MC samples for calibration available since last week

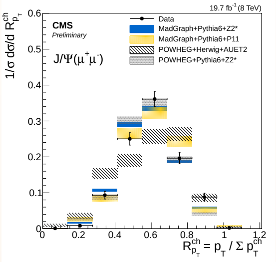


Figure 5: Normalized differential production cross-section of J/ψ candidates in $t\bar{t}$ events, as function of the relative p_T measured with respect to the jet axis direction.

CMS PAS TOP-13-007

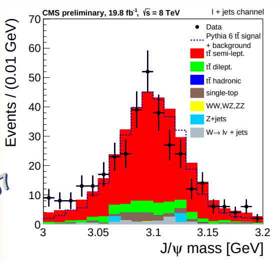
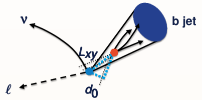


Figure 6: Di-muon invariant mass after requiring 1 isolated lepton (e or μ), a di-muon pair, and a jet criterion.

- Studies on b-fragmentation also on-going to reduce systematic uncertainties

B hadron lifetime technique (L_{xy})

- Selecting $t\bar{t}$ events among $\sqrt{s} = 8$ TeV data (19.6 fb^{-1})
  - events with 1 charge isolated lepton (e or μ), ≥ 4 jets
  - events with 1 electron, 1 muon, and ≥ 2 jets
- Based on the fact that, in the rest frame of the top-quark, the top-quark decay producs momenta are correlated to m_{top}
- Considering the B-hadron decay length L_{xy} to be analogously correlated to m_{top} as most of the energy is transfered from the b-quark to the B-hadron



- Selecting the secondary vertex with the largest L_{xy} and the median $\widehat{L_{xy}}$ of the distribution of secondary vertices with maximal L_{xy}
- Exploiting the linear dependency of $\widehat{L_{xy}}$ on the top-quark mass of $\mathcal{O}(0.0025 - 0.0030\text{ cm})$ per GeV/c^2

$m_{\text{top}} = 173.5 \pm 1.5$ (stat.) ± 1.3(syst.) ± 2.6 (p_T (t)) GeV/c^2

Main systematic uncertainties: background normalization, hadronization, p_T(t) modeling

CMS PAS TOP-12-030

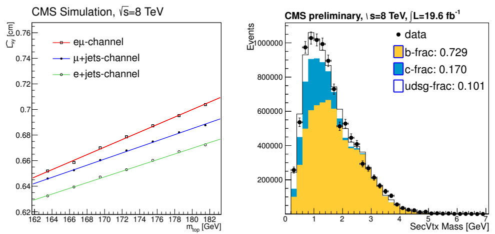
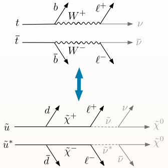


Figure 7: $\widehat{L_{xy}}$ as a function of m_{top} from simulation (left) and inclusive fit to the flavour content of a dijet sample based on the secondary vertex mass distribution (right).

Kinematic endpoint method

- Selecting dileptonic $t\bar{t}$ events among $\sqrt{s} = 7$ TeV data (5.0 fb^{-1})
- Testing mass determination method that may be used in beyond SM physics scenarios
  $\hookrightarrow$ topological resemblance: 2 cascade decays ending in invisible particles



  - Underconstrained system
    $\hookrightarrow$ μ_{bb}: variable designed on purpose, weakly-correlated to the invariant mass $M_{b\ell}$
  - μ_{bb}^{max} and $M_{b\ell}^{max}$ correlated to the top-quark mass
  - Assuming $m_\nu = 0$ and $M_W = 80.4$ GeV/c^2 in the joint unbinned likelihood fit procedure
- No MC calibration needed
- Main systematic uncertainties: fit range, JER

$$m_{top} = 173.9 \pm 0.9\ (\text{stat.})^{+1.7}_{-2.1}\ (\text{syst.})\ \text{GeV/c}^2$$

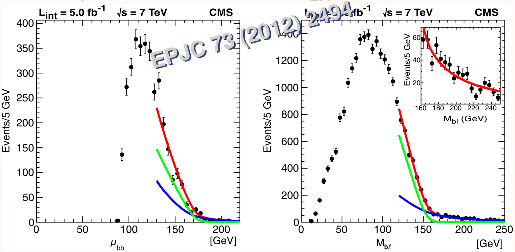


Figure 8: Simultaneous fit of the μ_{bb} (left) and $M_{b\ell}$ (right) distributions. The red line is the full fit, while the blue and green curves are for the background and signal shapes.

Using the stransverse mass

- Among $\sqrt{s} = 7$ TeV data (4.7 fb^{-1}), selecting $e^{\pm}\mu^{\mp}$ dileptonic $t\bar{t}$ events with ≥ 2 jets
- Defining the stransverse mass m_{T2}, a kinematic variable used in pair-production events where each parent particle decays into visible particles and one undetected particle (cf. Phys. Rev. D81 (2010) 031102)
  $\hookrightarrow$ $\vec{p}_T^{\,miss}$ and 4-vectors of the 2 leptons and 2 b-jets are used, m_ν is set to 0
- Using the dependence of the mean value $\bar{m}_{T2}$ of the m_{T2} distribution on the top-quark mass
  $\hookrightarrow$ MC samples with varied input m_{top}^{MC} are used to create a calibration curve

ATLAS CONF 2012-082

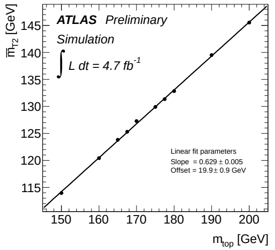


Figure 9: Calibration curve based on Monte Carlo simulation of $t\bar{t}$ events at different input top-quark masses including all expected backgrounds.

$$m_{top} = 175.2 \pm 1.6\,(\text{stat.})^{+3.1}_{-2.8}(\text{syst.})\ \text{GeV}/c^2$$

Main systematic sources:
JES, bJES, generator model,
and color reconnection

From the $t\bar{t}$ cross-section

Contribution from F. Déliot (IRFU)

- Using the measurement of $\sigma_{t\bar{t}}$ derived at $\sqrt{s} = 7$ TeV, through a multivariate analysis, from data collected in the $e^{\pm}\mu^{\mp}$ dileptonic channel (35 pb^{-1})
- Theoretical predictions at approximate NNLO or NLO+NNLL, dependence on m_{top}^{pole} described by a 3rd-order polynomial divided by $(m_{top}^{pole})^4$
- Using kinematical distributions from lepton and jet observables and information from b-tagging, feeding a profile likelihood

$$m_{top}^{pole} = 166.4^{+7.8}_{-7.3} \text{ GeV/c}^2$$

ATLAS CONF 2011-054

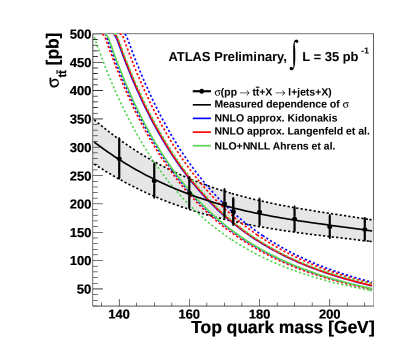


Figure 10: Comparison of the predicted cross-section and the experimentally measured cross-section as function of the top-quark mass.

From the $t\bar{t}$ cross-section

- Using the measurement of $\sigma_{t\bar{t}}$ derived at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV from data collected in the $e^{\pm}\mu^{\mp}$ dileptonic channel (4.6 fb^{-1} and 20.3 fb^{-1})
- Extraction performed by maximizing a Bayesian likelihood from the expected $\sigma_{t\bar{t}}$:
  - expected $\sigma_{t\bar{t}}$ calculated to NNLO by the program TOP++ 2.0
  - soft-gluon resummation being performed at NNLL accuracy
  - dependence on m_{top}^{pole} described by a 2nd-order polynomial divided by $(m_{top}^{pole})^4$

$$m_{top}^{pole} = 172.9\,^{+2.5}_{-2.6}\ \text{GeV/c}^2$$

EPJC 74 (2014) 3109

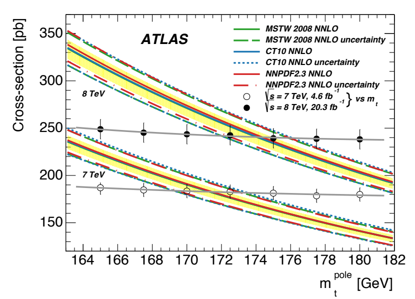


Figure 11: Predicted NNLO+NNLL $t\bar{t}$ production cross-section at 7 and 8 TeV as a function of the top-quark pole mass, using several PDF sets, compared to the cross-section measured by ATLAS assuming $m_{top} = m_{top}^{pole}$.

From the $t\bar{t}$ cross-section

- Using the measurement of $\sigma_{t\bar{t}}$ derived at $\sqrt{s} = 7$ TeV from data collected in the dileptonic decay channel (2.3 fb^{-1})
  → JHEP11 (2012) 067
- Constraining α_S at the scale of the Z-boson mass to the current world average and assuming that the measured $\sigma_{t\bar{t}}$ is not affected by non-SM physics
- Constructing a Bayesian prior from the expected $\sigma_{t\bar{t}}$:
  - expected $\sigma_{t\bar{t}}$ calculated to NNLO by the program TOP++ 2.0
  - soft-gluon resummation performed at NNLL accuracy
  - dependence on m_{top}^{pole} described by a 3rd-order polynomial divided by $(m_{top}^{pole})^4$

$$m_{top}^{pole} = 176.7\,^{+3.8}_{-3.4}\ \text{GeV/c}^2$$

PLB 728 (2013) 496

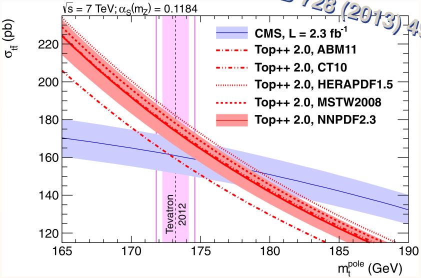


Figure 12: Predicted $t\bar{t}$ cross-section at NNLO+NNLL as a function of the top-quark pole mass, using 5 different NNLO PDF sets, compared to the cross-section measured by CMS assuming $m_{top} = m_{top}^{pole}$.

From the $t\bar{t}+$jet differential cross-section

ATLAS EXPERIMENT

ATLAS CONF 2014-053

- Among $\sqrt{s}=7$ TeV data (4.6 fb^{-1}), selecting semileptonic $t\bar{t}$ events with 1 lepton, ≥ 2 b-tagged jets, ≥ 3 other non b-tagged jets
- Based on the large dependence of gluon radiation on m_{top}
- Measuring the differential cross-section of top-quark pair production in association with a high-p_T jet:

$$\mathcal{R}(m_{top}^{pole},\rho_s)=\frac{1}{\sigma_{t\bar{t}+jet}}\frac{d\sigma_{t\bar{t}+jet}}{d\rho_s}$$

with $\rho_s=2m_0/\sqrt{s_{t\bar{t}+jet}}$,

- Correcting for detector effects and hadronization after background subtraction
- Comparing to NLO+PS prediction using the least square method

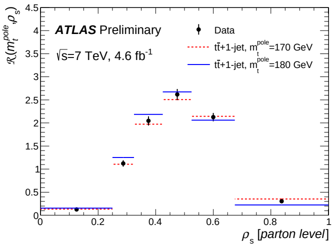


Figure 13: $\mathcal{R}$-distribution at parton level corrected for detector and hadronizaton effects after the background subtraction.

$$m_{top}^{pole}=173.7\pm1.5\,(\text{stat.})\pm1.4(\text{syst.})^{+1.0}_{-0.5}(\text{theo.})\ \text{GeV}/c^2$$

Main systematic uncertainties: JES and ISR/FSR

Conclusion and outlook

- Plenty more data to be taken in the next years:
  - Using 5 fb^{-1} of data at $\sqrt{s} = 7$ TeV as a baseline for the projection
  - Assuming cross-section increase compensates trigger efficiency decrease
  - Assuming detector upgrade helps keeping PU under control
  - Assuming data constrain systematic sources
- NLO-multileg generators expected to provide a finer description
- b-JES, soft QCD, and more generally models expected to be better constrained by data

CMS PAS FTR-13-017

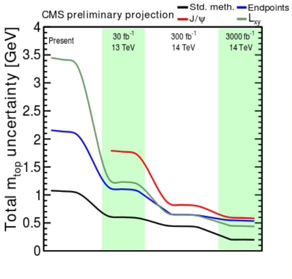


Figure 14: Projection of the top-quark-mass precision obtained with different measurement methods, for various integrated luminosity.

For more top-quark related results from the ATLAS collaboration:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
For more top-quark related results from the CMS collaboration:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Backup

Using the b-jet energy spectrum

Phys.Rev. D88 (2013) 5, 057701

- The E_b^{lab} distribution is peaking at:

$$E_b^{rest} = \frac{m_{top}^2 - m_W^2 + m_b^2}{2m_{top}}$$

robust wrt $\sqrt{s}$, top-quark boost, and ISR variations

- Generating pseudo-experiments for $e^{\pm}\mu^{\mp}$ $t\bar{t}$ events at $m_{top}^{MC} = 173$ GeV/c^2, assuming a luminosity of 5 fb^{-1} at $\sqrt{s} = 7$ TeV
- Fitting $x = E_b^{lab}/E_b^{rest}$ with:

$$f(x) = K_1^{-1}(p)\exp\left[-\frac{p}{2}\left(x + \frac{1}{x}\right)\right],$$

p being a parameter and $K_1(p)$ a modified Bessel function

- Purely kinematic method, needing precise detection of only one decay product

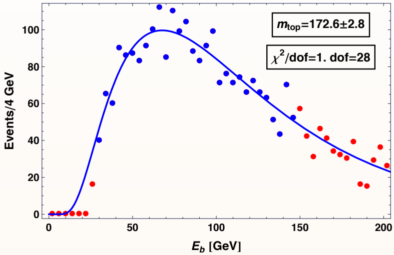
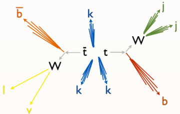


Figure 15: Fit of the energy distribution of the b-jets in a pseudo-experiment between 30 and 150 GeV.

For 100 pseudo-experiments, using the Delphes 1.9 detector simulation: $\langle m_{top} \rangle = 173.1 \pm 2.5$ GeV/c^2

Bi-Event Subtraction Technique (BEST)

- testing mass determination method that may be used in beyond SM physics scenarios
- subtracting combinatorial background due to inclusion of particles which do not come from the cascade decay of interest
  ↪ combining jet information from a different event several times for the same decay chain reconstruction
  - m_{jj}^{same} dijet invariant mass distribution from one sample
  - m_{jj}^{bi} dijet invariant mass distribution from a bi-event sample not coming from a W
  - $m_{jj}^{BEST} = m_{jj}^{same} - C_{jj}^{BEST} \cdot m_{jj}^{bi}$ showing a W-boson mass peak almost without combinatorial background



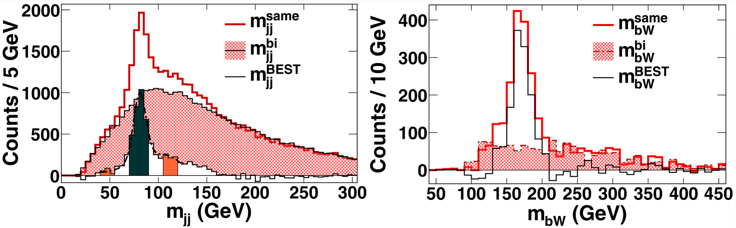


Figure 16: Dijet invariant mass distribution (left) and W+b invariant mass distribution (right) using BEST.

Phys. Lett. B 703:475 (2011)

Systematic uncertainties (1)

Source		Δm_t[GeV]		
		μ+jets	e+jets	$e\mu$
Statistical		1.0	1.0	2.0
Experimental	Jet energy scale	0.30 ± 0.01	0.30 ± 0.01	0.30 ± 0.01
	Multijet normalization (ℓ+jets)	0.50 ± 0.01	0.67 ± 0.01	-
	W+jets normalization (ℓ+jets)	1.42 ± 0.01	1.33 ± 0.01	-
	DY normalization ($\ell\ell$)	-	-	0.38 ± 0.06
	Other backgrounds normalization	0.05 ± 0.01	0.05 ± 0.01	0.15 ± 0.07
	W+jets background shapes (ℓ+jets)	0.40 ± 0.01	0.20 ± 0.01	-
	Single top background shapes	0.20 ± 0.01	0.20 ± 0.01	0.30 ± 0.06
	DY background shapes ($\ell\ell$)	-	-	0.04 ± 0.06
	Calibration	0.42 ± 0.01	0.50 ± 0.01	0.21 ± 0.01
Theory	Q^2-scale	0.47 ± 0.13	0.20 ± 0.03	0.11 ± 0.08
	ME-PS matching scale	0.73 ± 0.01	0.87 ± 0.03	0.44 ± 0.08
	PDF	0.26 ± 0.15	0.26 ± 0.15	0.26 ± 0.15
	Hadronization model	0.95 ± 0.13	0.95 ± 0.13	0.67 ± 0.10
	B hadron composition	0.39 ± 0.01	0.39 ± 0.01	0.39 ± 0.01
	B hadron lifetime	0.29 ± 0.18	0.29 ± 0.18	0.29 ± 0.18
	Top quark p_T modeling	3.27 ± 0.48	3.07 ± 0.45	2.36 ± 0.35
	Underlying event	0.27 ± 0.51	0.25 ± 0.48	0.19 ± 0.37
	Colour reconnection	0.36 ± 0.51	0.34 ± 0.48	0.26 ± 0.37

Figure 17: Statistical, experimental and theoretical systematic uncertainties on m_{top} for the B hadron lifetime technique (CMS PAS TOP-12-030).

Systematic uncertainties (2)

	Value [GeV]
Measured value	172.2
Statistical uncertainty	0.7
Jet energy scale	1.5
Jet energy resolution	< 0.1
Jet vertex fraction	< 0.1
Flavour tagging efficiency	0.3
Electron uncertainties	0.3
Muon uncertainties	0.1
Missing transverse momentum	0.2
W+jets normalisation	0.4
W+jets shape	0.3
Z+jets/diboson normalisation	0.2
Multijet normalisation	0.2
Multijet shape	0.3
Top normalisation	0.2
t-channel generator	< 0.1
t-channel hadronisation	0.7
t-channel colour reconnection	0.3
t-channel underlying event	< 0.1
tt,Wt, and s-channel generator	0.2
tt hadronisation	< 0.1
tt colour reconnection	0.2
tt underlying event	0.1
tt ISR/FSR	0.2
Proton PDF	< 0.1
Simulation sample statistics	0.3
Total systematic uncertainty	2.0
Total uncertainty	2.1

Figure 18: Statistical and systematic uncertainties on m_{top} using single-top enhanced topologies (ATLAS CONF 2014-055).

Source	Uncertainty [GeV]
$t\bar{t}$ generator model	−1.3 / +1.3
Parton shower	−0.9 / +0.9
Colour reconnection	−1.2 / +1.2
ISR/FSR	−0.5 / +0.5
PDF	−0.1 / +0.1
Fakes norm. and shape	−0.3 / +0.3
Calibration curve	−0.3 / +0.3
Underlying event	−0.2 / +0.2
Jet energy scale	−1.4 / +1.6
b-jet energy scale	−1.2 / +1.5
Jet energy resolution	−0.5 / +0.5
Leptons	−0.1 / +0.2
$E_{\text{T}}^{\text{miss}}$ and jets	−0.1 / +0.1
b-tagging	−0.4 / +0.3
Syst. uncertainty	−2.8 / +3.1
Stat. uncertainty	−1.6 / +1.6
Total uncertainty	−3.3 / +3.5

Figure 19: Statistical and systematic uncertainties on m_{top} using the stransverse mass (ATLAS CONF 2012-082).

Systematic uncertainties (3)

Description	Value [GeV]
Measured value	173.09
Statistical uncertainty	0.64
Method calibration	0.07
Signal MC generator	0.20
Hadronisation	0.44
Underlying event	0.42
Colour reconnection	0.29
ISR/FSR	0.37
Proton PDF	0.12
Background	0.14
Jet energy scale	0.89
b-jet energy scale	0.71
b-tagging efficiency and mistag rate	0.46
Jet energy resolution	0.21
Missing transverse momentum	0.05
Pile-up	0.01
Electron uncertainties	0.11
Muon uncertainties	0.05
Total systematic uncertainty	1.50
Total uncertainty	1.63

Figure 20: Systematic and statistical uncertainties on m_{top} using $m_{\ell b}$ (arXiv:1503.05427).

Source	Value [GeV]
Jet energy scale	${}^{+0.5}_{-1.4}$
Fit range	± 0.6
Jet energy resolution	± 0.5
Background modeling	± 0.5
Efficiency	${}^{+0.1}_{-0.2}$
Color reconnection	± 0.6
Syst. uncertainty	${}^{+1.2}_{-1.8}$
Stat. uncertainty	± 0.9

Figure 21: Systematic and statistical uncertainties on m_{top} for the kinematic endpoint method (EPJC 73 (2012) 2494).

The top-quark mass in the Standard Model:

How fundamental is this parameter ?

- key role in the prediction of many observables either directly or via electroweak radiative corrections
  $\hookrightarrow BR(\mathrm{B_s} \to \mu^+\mu^-)$, $m_\mathrm{W} = f(m^2_\mathrm{top}, \ln m_\mathrm{H})$
- key input to electroweak fit, which enables comparisons between experimental results and predictions within and beyond the SM
- highest Yukawa coupling to the Higgs boson: probe for the stability of the electroweak vacuum and Higgs boson properties

http://cern.ch/Gfitter

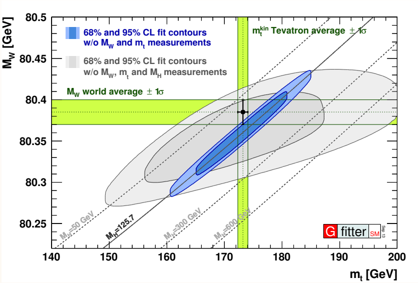


Figure 22: Contours of 68% and 95% confidence level obtained from scans of fits with fixed variable pairs M_W vs m_top. The narrower blue and larger grey allowed regions are the results of the fit including and excluding the M_H measurements respectively.