Top quark mass measurements at ATLAS and CMS

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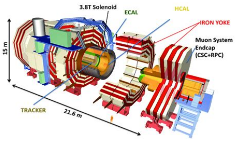
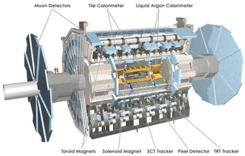
The top quark mass at the LHC

The top quark mass m_t is an important input to global fits of the Standard Model of particle physics and due to its high value connected to i.e. the Higgs and vacuum stability.

The latest measurements of m_t are done at the Large Hadron Collider by the experiments ATLAS and CMS.

Those two experiments are the only ones that can verify their respective measurements at $\sqrt{s} = 13\,\mathrm{TeV}$, the only other experiments that measured m_t with similar methods are DØ and CDF.

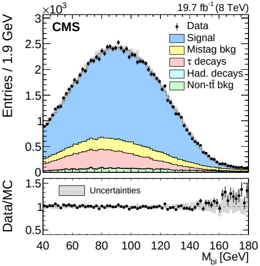


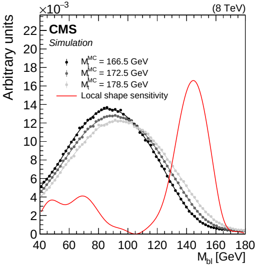


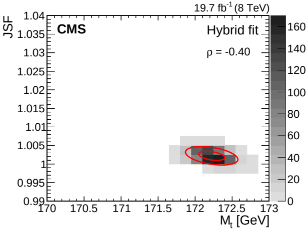
Direct Measurements

- select $t(\bar{t})$ decay channel and associated phase-space
- build templates of sensible observables from simulation (i.e. 3-jet mass)
- fit these templates to data to extract m_t

figures from PRD 96 (2017) 32





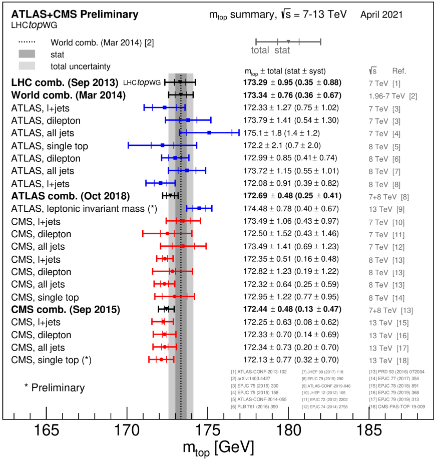


typical decay channels are:

- $t\bar{t} \to$ jets (two b-tagged jets and veto on leptons)
- $t\bar{t} \to 1$ lepton + jets (2 b-tagged jets and one electron or muon, veto on add. leptons)
- $t\bar{t} \to 2$ leptons + jets (2 b-tagged jets and two opposite sign leptons)
- single top
- $t\bar{t}$ decay associated with add. jets or leptons (i.e. from B-hadron decay)

all analyses presented in this talk only consider electrons and muons as leptons

Typical Leading Uncertainties



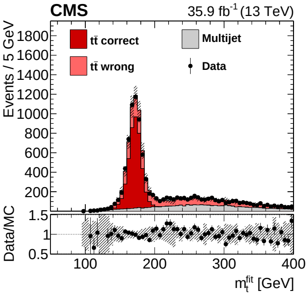
- Jet energy scale and resolution in the detector
- Modeling in simulation (choice of MC generator, color reconnection modelling, ...)
- Jet flavor dependency (tagging, flavor dependent jet energy scale, ...)

i.e. ATLAS, CMS, DØ, CDF combination (ATLAS-CONF-2014-008) relative uncertainties to 0.76 GeV: 35% stat., 31% in-situ JSF, 33% bJES, 50% MC, 41% CR

All Jets

CMS EPJC 79 (2019) 313

- kinematic fit to reconstruct $t\bar{t}$ system and suppress background
- simultaneously fitting an additional jet energy scale factor (JSF) via m_W^{reco} distribution



PRD93(2016)72, 8 TeV:

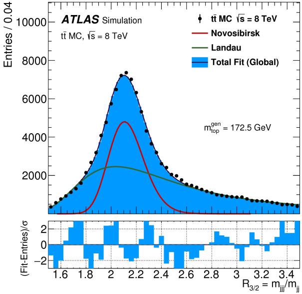
$m_t = 172.32 \pm 0.25 \pm 0.59$ GeV

EPJC79(2019)313, 13 TeV:

$m_t = 172.34 \pm 0.20 \pm 0.70$ GeV

ATLAS JHEP 09 (2017) 118

- template is derived from the ratio of the three-jet to the dijet mass



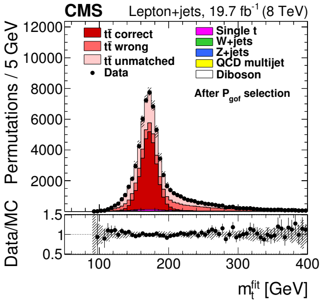
JHEP09(2017)118, 8 TeV:

$m_t = 173.72 \pm 0.55 \pm 1.01$ GeV

One Lepton + Jets

CMS PRD 93 (2016) 72

- single most precise measurement
- with kinematic fit and in-situ JSF fit



PRD93(2016)72, 8 TeV:

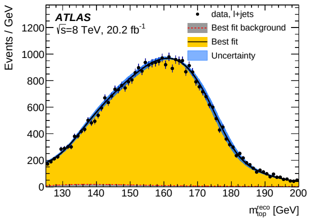
$m_t = 172.38 \pm 0.16 \pm 0.49$ GeV

EPCJ87(2018)891, 13 TeV:

$m_t = 172.25 \pm 0.08 \pm 0.62$ GeV

ATLAS EPJC 79 (2019) 290

- three-dimensional template (m_{top}^{reco}, m_W^{reco}, R_{bq}^{reco})
- in-situ JSF constrain and relative b-to-light-jet energy scale factor



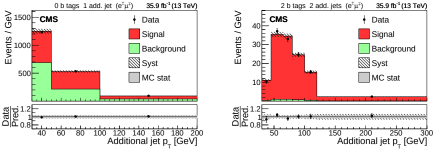
EPJC79(2019)290, 8 TeV:

$m_t = 172.08 \pm 0.39 \pm 0.8$ GeV

Two Leptons + jets

CMS EPJC 79 (2019) 368

- simultaneous fit with the cross section
- categorize events by number of b-tagged and additional jets for template



PRD93(2016)72, 8 TeV:

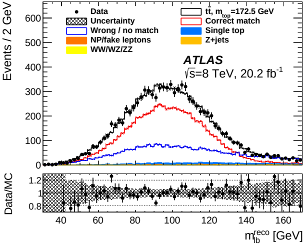
$m_{\mathrm{t}} = 172.82 \pm 0.19 \pm 1.22$ GeV

EPJC79(2019)368, 13 TeV:

$m_{\mathrm{t}} = 172.33 \pm 0.14^{+0.66}_{-0.72}$ GeV

ATLAS PLB 761 (2016) 350

- includes the lepton–b-jet invariant mass distribution as additional template



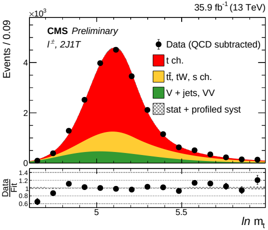
PLB761(2016)350, 8 TeV:

$m_{\mathrm{t}} = 172.99 \pm 0.41 \pm 0.74$ GeV

Single Top (One Lepton+Jets)

CMS CMS-PAS-TOP-19-009 (submitted to JHEP)

- uses MVA to separate signal from background with high purity
- also measured t to $\bar{\mathrm{t}}$ mass ratio $(0.9952^{+0.0079}_{-0.0104})$ and difference $(0.83^{+1.79}_{-1.35}$ GeV)



EPJC77(2017)354, 8 TeV:

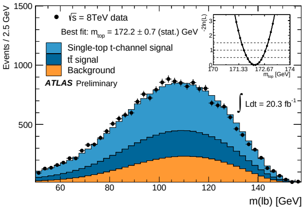
$m_{\mathrm{t}} = 172.95 \pm 0.77 \pm 0.95$ GeV

CMS-PAS-TOP-19-009, 13 TeV:

$m_{\mathrm{t}} = 172.13 \pm 0.32 \pm 0.70$ GeV

ATLAS ATLAS-CONF-2014-055

- uses MVA to separate signal from background with high purity
- includes the lepton–b-jet invariant mass distribution as additional template



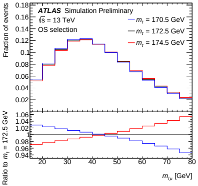
ATLAS-CONF-2014-055, 8 TeV:

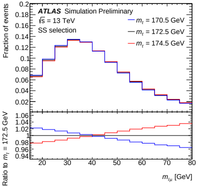
$m_{\mathrm{t}} = 172.2 \pm 0.7 \pm 2.0$ GeV

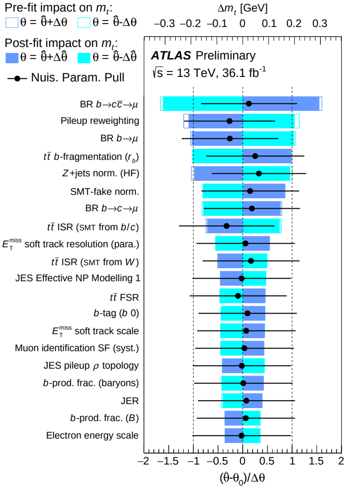
Via Leptonic Invariant Mass

ATLAS ATLAS-CONF-2019-046 (preliminary)

- uses semi-leptonic decays of b-hadrons produced in the top-quark decay
- SMT (soft muon tagger) tagging is performed, optimized to select muons originating from the semileptonic decays of b hadrons
- the distribution of the invariant mass $m_{l,\mu}$ between the lepton from the W-boson decay and the μ from the b-hadron decay is used as template
- same- and opposite-sign contribute differently







13 TeV: $m_t = 174.48 \pm 0.40(\text{stat.}) \pm 0.67(\text{syst.})$ GeV

Indirect Measurements / Pole Mass

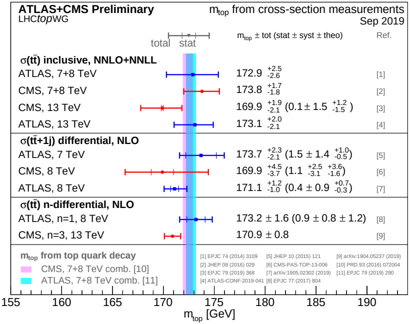
The direct methods extract "only" the parameter m_t^{MC} as defined in simulation.

This parameter can be identified as the pole mass m_t^{pole}, but only with an (additional) uncertainty $|m_t^{\mathrm{MC}} - m_t^{\mathrm{pole}}| \sim 0.5\,\mathrm{GeV}$, this is reviewed in ARNPS 70 (2020) p.225-255

Extract the pole mass via a theoretical well described quantity like the cross-section.

A differential cross-section is determined.

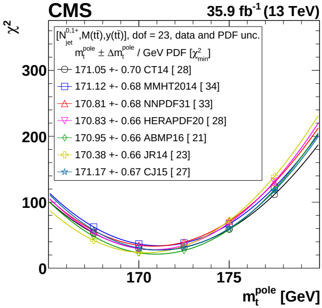
This method yields larger errors than direct measurements due to the uncertainty in cross section normalization.



Via Cross-Section

CMS EPJC 80 (2020) 658

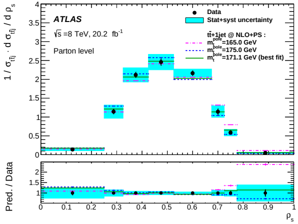
- using events containing two oppositely charged leptons
- 3D $t\bar{t}$ production cross-section using NLO calculations and a simultaneous fit of α_s



13 TeV: $m_t^{\text{pole}} = 170.5 \pm 0.8\,\text{GeV}$

ATLAS JHEP 11 (2019) 150

- using events containing one lepton and one additional jet
- differential in $\rho_s = \frac{2m_0}{m_{t\bar{t}+1\text{-jet}}}\Big|_{m_0=170\,\text{GeV}}$

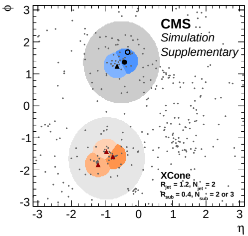


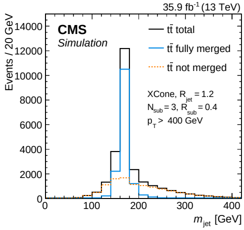
8 TeV: $m_t^{\text{pole}} = 171.1^{+1.2}_{-1.0}\,\text{GeV}$

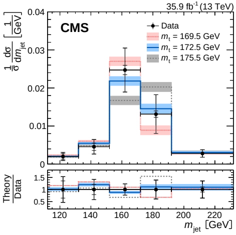
Boosted Top (One Lepton + Jets)

CMS PRL 124 (2020) 20

- hadronic top quark decay is reconstructed as a single jet with $p_T > 400\,\mathrm{GeV}$
- use XCone jet algorithm (JHEP 11 (2015)072) to reconstruct fat jets with 3 subjets
- extract m_t^{pole} via unfolding of the jet mass differential cross-section





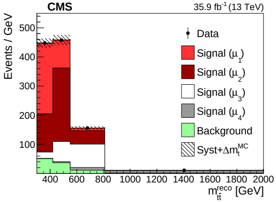


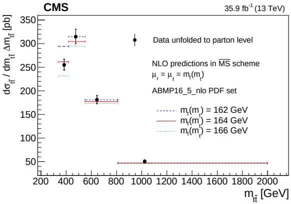
13 TeV: $m_t = 172.6 \pm 0.4(\mathrm{stat.}) \pm 1.6(\mathrm{exp.}) \pm 1.5(\mathrm{model.}) \pm 1.0(\mathrm{theo.})\,\mathrm{GeV}$

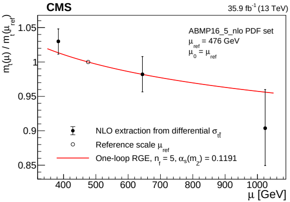
Running of the top mass

CMS PLB 803 (2020) 135263

- using $t\bar{t}$ candidate events in the $e^{\pm}\mu^{\mp}$ channel
- measure four $\sigma_{t\bar{t}}$ values in different scales $\mu_k = \langle m_{t\bar{t}} \rangle_k |_{k \in 1-4}$
- extract $m_t^{\overline{MS}}$ from comparison of the $\sigma_{t\bar{t}}$ values to NLO theoretical predictions.
- the running is probed up to a scale of the order of 1 TeV







No-running hypothesis excluded at 95%CL

Summary and Outlook

Continuous campaign of measurements by ATLAS/CMS led to a precision of <0.5 GeV ($<0.3\%$):
CMS (Sep. 2015): $m_{\mathrm{t}} = 172.44 \pm 0.13(\mathrm{stat.}) \pm 0.47(\mathrm{syst.})$ GeV
ATLAS (Oct. 2018): $m_{\mathrm{t}} = 172.69 \pm 0.25(\mathrm{stat.}) \pm 0.41(\mathrm{syst.})$ GeV

- m_{t} measurements are limited by systematic uncertainty and will soon be limited by relating the simulation parameter to a theoretical well described quantity

The uncertainty is expected to decrease in the near future due to:

- novel likelihood methods including additional observables and a description of the uncertainties as part of the likelihood
- full Run2 LHC combination