Recent measurements of the top-quark mass using the ATLAS detector at the LHC

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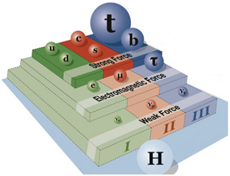
Physics motivations

Why top-quark physics?

- Heaviest elementary particle known.

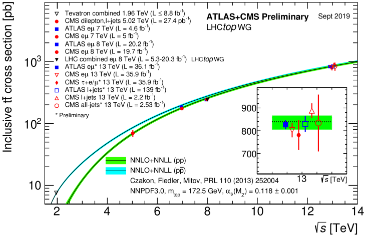
$$m_t = 173.34 \pm 0.27(stat) \pm 0.71(syst)\ \text{GeV}$$



- Its large mass is a fundamental parameter in the Standard Model ⇒ highest coupling to the Higgs boson.

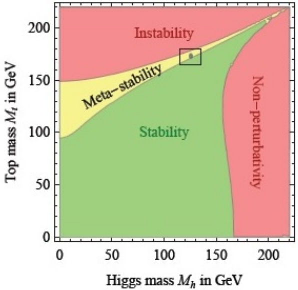
- Due to its very short lifetime, the top-quark decays before hadronizing: $t \Rightarrow Wb \sim 10^{-24}s$ vs hadronization $\sim 10^{-23}s$ ⇒ allows to study the properties of a bare quark.

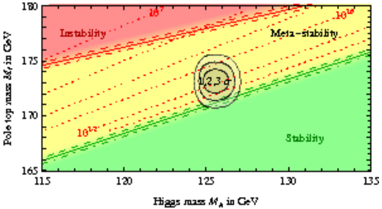
- LHC is a top quark factory, large pair production cross-section.



Why measure the top-quark mass?

- The top-quark mass is a fundamental parameter of the Standard Model:
  - Electroweak precision tests.
  - Constrained the mass of the Higgs boson (before its discovery at the LHC).
  - Stability of the Standard Model vacuum.
    - The measured values of m_H and m_t place the SM vacuum at the border between stability and metastability JHEP08(2012)098.

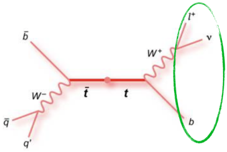




Methods to measure the top-quark mass

Direct m_t measurement:

- Extraction from kinematic reconstruction of the invariant mass of top quark decay products ("Standard method").
- Data compared to MC simulations with different input values of m_t.
- Relying on jets, parton showers (LO), non-perturbative effects.
  - Still controversial argument (see arXiv:1712.02796).



Indirect m_t measurement:

- Measurement from cross-sections (inclusive/differential).
  - In a well defined renormalization scheme, e.g. m_t^{pole} (definition of free particle mass).
- $\mathcal{O}(1\text{GeV})$ $|m_t^{MC}$ - $m_t^{pole}|$ Nucl.Phys.Proc.Suppl. 185(2008) 220-226.

m_t^{pole} using $t\bar{t}$+1-jet with the ATLAS experiment (8 TeV pp collisions) JHEP11(2019)150

m_t^{pole} from $t\bar{t}$+1-jet production : Analysis strategy

Indirect measurement of m_t^{pole} from differential cross-sections measurement of $t\bar{t}$+1-jet production.

- Data collected by the ATLAS detector at 8 TeV of *pp* collisions ($\mathcal{L} = 20.2\ fb^{-1}$)
- $\sigma_{t\bar{t}+1-\mathrm{jet}}$ is more sensitive than $\sigma_{t\bar{t}}$ (gluon radiation depends on the mass of the quarks).

Method to extract m_t^{pole}:

- Measure normalised $t\bar{t}$+1-jet differential distribution, as a function of the invariant mass of the $t\bar{t}$+1-jet system ($m_{t\bar{t}+1-\mathrm{jet}}$).
- Compare the unfolded distribution at parton level to NLO+PS $t\bar{t}$+1-jet calculations.

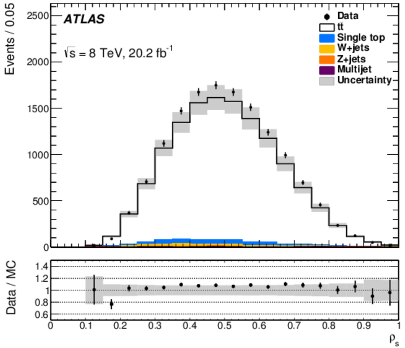
$$\mathcal{R}(m_t^{pole},\rho_s)=\frac{1}{\sigma_{t\bar{t}+1-\mathrm{jet}}}\frac{d\sigma_{t\bar{t}+1-jet}}{d\rho_s}(m_t^{pole},\rho_s),\quad \rho_s=\frac{340\,GeV}{m_{t\bar{t}+1-\mathrm{jet}}}$$

m_t^{pole} from $t\bar{t}$+1-jet production: Objects definition reconstruction

Event selection and reconstruction:

- Exactly 1 reconstructed e or μ.
- $>=$ 5 jets (anti-k_t jet reconstruction algorithm).
- The extra jet is the leading jet with $p_T > 50$ GeV and $|\eta| < 2.5$.
  - Not used in the $t\bar{t}$ reconstruction.

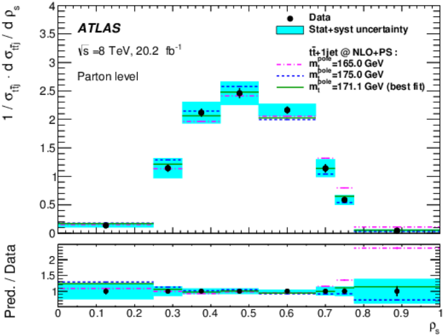
Channel	e+jets	μ+jets
$t\bar{t}$	5530 ± 470	7080 ± 600
Single top	191 ± 15	226 ± 18
W+jets	100 ± 33	121 ± 37
Z+jets	24 ± 8	13 ± 4
Multijet	21 ± 11	<11
Prediction	5870 ± 540	7440 ± 660
Data	6379	7824



- Signal purity of $\sim$ 94% for the e+jets channel and $\sim$ 95% for the μ+jets.

m_t^{pole} from $t\bar{t}$+1-jet production: Top quark mass determination

- Unfolding at parton level.
- m_t^{pole} extracted by fitting the $\mathcal{R}$ distribution with the NLO+PS fixed-order predictions (POWHEG+PYTHIA6).



The least-squares method is used, the fit minimize a χ^2:

$$\chi^2 = \sum_{ij} (\mathcal{R}_i^{data} - \mathcal{R}_i^{theory}(m_t^{pole})) V_{ij}^{-1} (\mathcal{R}_j^{data} - \mathcal{R}_j^{theory}(m_t^{pole}))$$

m_t^{pole} from $t\bar{t}$+1-jet production: Results

Mass scheme	m_t^{pole} [GeV]	$m_t(m_t)$ [GeV]
Value	**171.1**	**162.9**
Statistical uncertainty	**0.4**	**0.5**
Simulation uncertainties		
Shower and hadronisation	0.4	0.3
Colour reconnection	0.4	0.4
Underlying event	0.3	0.2
Signal Monte Carlo generator	0.2	0.2
Proton PDF	0.2	0.2
Initial- and final-state radiation	0.2	0.2
Monte Carlo statistics	0.2	0.2
Background	<0.1	<0.1
Detector response uncertainties		
Jet energy scale (including b-jets)	0.4	0.4
Jet energy resolution	0.2	0.2
Missing transverse momentum	0.1	0.1
b-tagging efficiency and mistag	0.1	0.1
Jet reconstruction efficiency	<0.1	<0.1
Lepton	<0.1	<0.1
Method uncertainties		
Unfolding modelling	0.2	0.2
Fit parameterisation	0.2	0.2
Total experimental systematic	**0.9**	**1.0**
Scale variations	(+0.6, −0.2)	(+2.1, −1.2)
Theory PDF⊕α_s	0.2	0.4
Total theory uncertainty	**(+0.7, −0.3)**	**(+2.1, −1.2)**
Total uncertainty	**(+1.2, −1.1)**	**(+2.3, −1.6)**

Modelling

Detector

Theory

Dominant uncertainties:

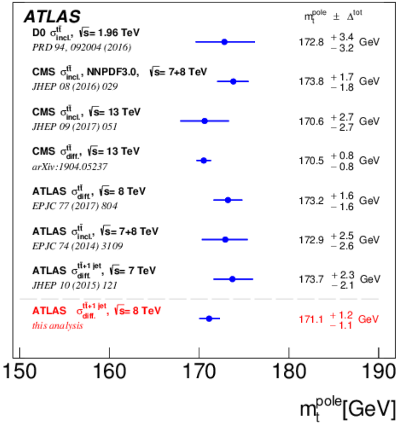
- JES
- PS and hadronisation
- Color reconnection
- Scale variation

$$m_t^{pole} = 171.1 \pm 0.4(stat) \pm 0.9(syst)^{+0.7}_{-0.3}(theo)\,\mathrm{GeV}$$

$$m_t(m_t) = 162.9 \pm 0.5(stat) \pm 1.0(syst)^{+2.1}_{-1.2}(theo)\,\mathrm{GeV}$$

Total uncertainty: $\Delta m_t^{pole} = ^{+1.2}_{-1.1}$ GeV

m_t^{pole} summary



m_t^{pole} extraction @ 13 TeV (dilepton channel) on Teng Jian Khoo's talk from yesterday.

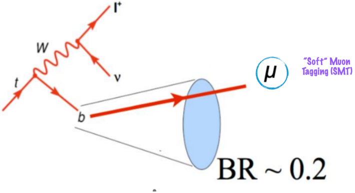
- m_t^{pole} result obtained from data unfolded to parton level is compatible with previous measurements.
- Statistical and systematic uncertainties reduced of a factor 2 w.r.t 7 TeV measurement ▸ JHEP10(2015)121.

Top-quark mass using a leptonic invariant mass with the ATLAS experiment (13 TeV *pp* collisions) ▸ ATLAS-CONF-2019-046

Soft Muon Tagging m_t: analysis strategy

Direct measurement of m_t in the $t\bar{t} \to \ell +$ jets channel with an experimental technique which exploits semileptonic decays of b-hadrons produced in the top-quark decay chain.

- Data collected by the ATLAS detector at 13 TeV of pp collisions ($\mathcal{L} = 36.1\ \text{fb}^{-1}$).

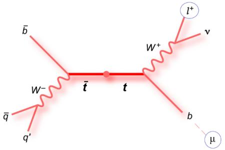


- "Standard method": $m_{\ell b} \to m_t$.
- "Experimental method": semi leptonic decay of B-hadrons $m_{\ell\mu} \to m_t$.
  - purely leptonic, less sensitive to jets uncertainty.

1st proof of principle: CDF ▸ Phys. Rev. D80 (2009) 051104, m_t=180.5 ± 12.5 GeV

Similar idea: with $J/\psi \to \mu\mu$ from CMS ▸ JHEP 12 (2016) 123 , m_t=173.5 ± 3.1 GeV

Soft Muon Tagging m_t: event selection and reconstruction

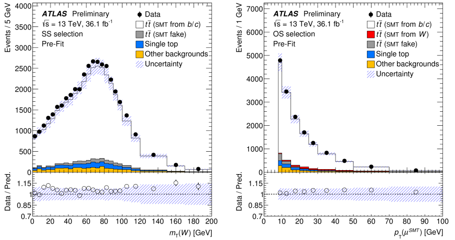


Event selection:

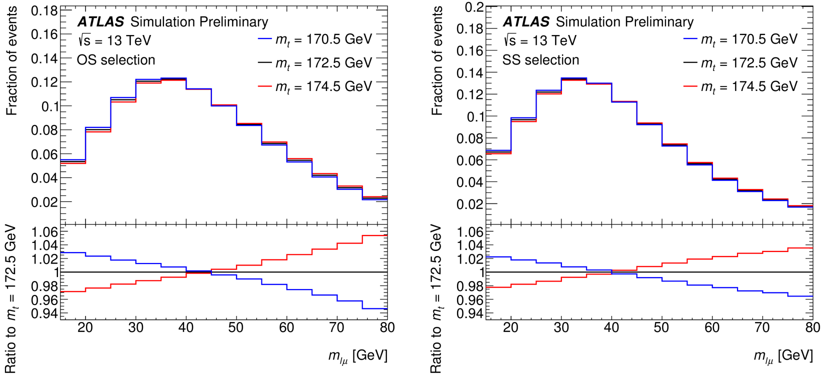
- Exactly 1 isolated e or μ.
- Cuts on E_T^{miss} and M_T^W.
- $\geq$ 4 jets.
- $\geq$ 1 b-jet, 77% efficiency WP.
- $\geq$ 1 SMT jet (i.e. μ with $p_T > 8$ GeV found within $\Delta R < 0.4$ of a jet.).

Process	Yield (OS)	Yield (SS)
$t\bar{t}$ (SMT from b- or c-hadron)	56 000(4000)	34 800(2800)
$t\bar{t}$ (SMT from $W \to \mu\nu$)	2190(320)	4.9(36)
$t\bar{t}$ (SMT fake)	1490(210)	1240(170)
Single top t-chan	770(70)	490(40)
Single top s-chan	63(6)	49(4)
Single top Wt	1840(140)	1260(100)
W+jets	1600(400)	1080(240)
Z+light jets	210(80)	15(6)
Z+HF jets	550(170)	310(100)
Diboson	17.2(29)	6.3(14)
Multi-jet	530(140)	480(130)
Total Expected	65 000(5000)	39 800(3000)
Data	66 891	42 087

$\sim$ 86% signal purity

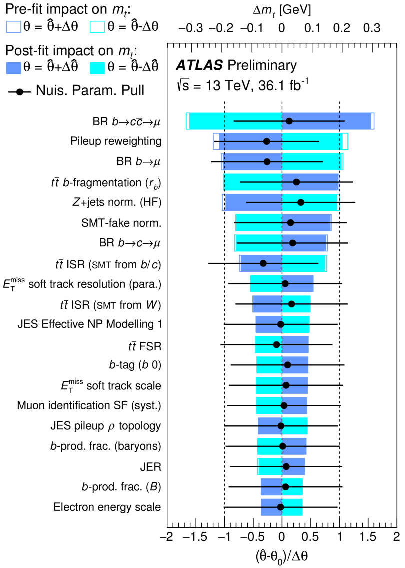


Soft Muon Tagging m_t: mass extraction



- Profiled Binned likelihood template fit in the 15-80 GeV region of $m_{\ell\mu}$.
  - Systematic uncertainties used as nuisance parameters.
- Higher sensitivity of OS region to m_t well visible.

Soft Muon Tagging m_t: fit results



- BR b$\to c\bar{c} \to \mu$
    - 20% uncertainty from direct meas.
- Pile-up reweighting
- BR b $\to \mu$: affects composition
- r_b: impacts fragmentation

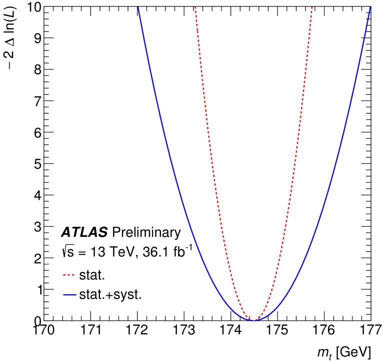
Soft Muon Tagging m_t: systematic uncertainties

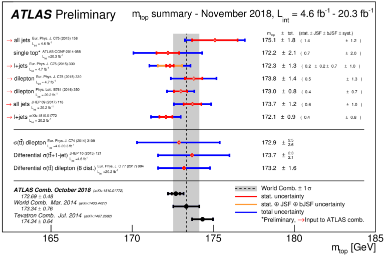
Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Data statistics	0.40	
Signal and background model statistics	0.16	
Monte Carlo generator	0.04	±0.07
Parton shower and hadronisation	0.07	±0.07
Initial-state QCD radiation	0.17	±0.07
Parton shower α_S^{FSR}	0.09	±0.04
b-quark fragmentation	0.19	±0.02
HF-hadron production fractions	0.11	±0.01
HF-hadron decay modelling	0.39	±0.01
Underlying event	< 0.01	±0.02
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.06	±0.01
W/Z+jets modelling	0.17	±0.01
Single top modelling	0.01	±0.01
Fake lepton modelling ($t \to W \to \ell$)	0.06	±0.02
Soft muon fake modelling	0.15	±0.03
Jet energy scale	0.12	±0.02
Soft muon jet p_T calibration	< 0.01	±0.01
Jet energy resolution	0.07	±0.05
Jet vertex tagger	< 0.01	±0.01
b-tagging	0.10	±0.01
Leptons	0.12	±0.00
Missing transverse momentum modelling	0.15	±0.01
Pile-up	0.20	±0.05
Luminosity	< 0.01	±0.01
Total systematic uncertainty	0.67	±0.04
Total uncertainty	0.78	±0.03

Dominant uncertainties from modelling:

- HF-hadron decays
- b-quark frag: r_b unc
- ISR
- Pile-up reweighting

Soft Muon Tagging m_t: results



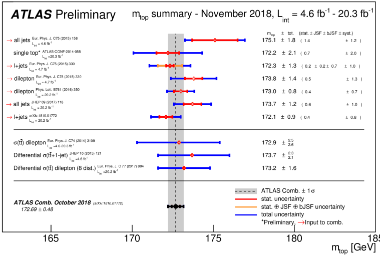


$$m_t = 174.48 \pm 0.40(stat) \pm 0.67(syst)\mathrm{GeV} = 174.48 \pm 0.78\mathrm{GeV}$$

Precise measurement, competitive with "standard" direct techniques!

Conclusions

- m_t is a key parameter in the SM and BSM physics, it is known with high precision.
- m_t is investigated within a variety of approaches.
- Cross section measurements are being used to perform an Indirect measurement of m_t^{pole}.
- Experimental technique which exploits semileptonic decays of b-hadrons used to perform a direct measurement the top quark mass.
- All those methods provide precise measurements of the top-quark mass compatible with previous results.



Thanks for the attention!

BACKUP

Relation between $\overline{MS}$ mass $m_t(\mu)$ and pole mass m_t^{pole}

- The QCD relation between the 2 schemes is known to four loops.
- Here truncated at two loops to match the precision of the $t\bar{t}+$ 1-jet cross section used to extract the mass in both schemes.

$$m_t^{pole} = m_t(m_t)\left(1 + \frac{4}{3}\frac{\alpha_s(\mu = m_t)}{\pi}\right) + \mathcal{O}(\alpha_s^2)$$

The pole mass result is obtained for α_s (163 GeV) ~ 0.116

- When converting $m_t(m_t)$ to m_t^{pole} the obtained value is $\approx$ 170.9 GeV.
  - Good agreement with the direct extraction of m_t^{pole}.