Measurements of the top-quark mass using the ATLAS detector at the LHC

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on behalf of the ATLAS collaboration

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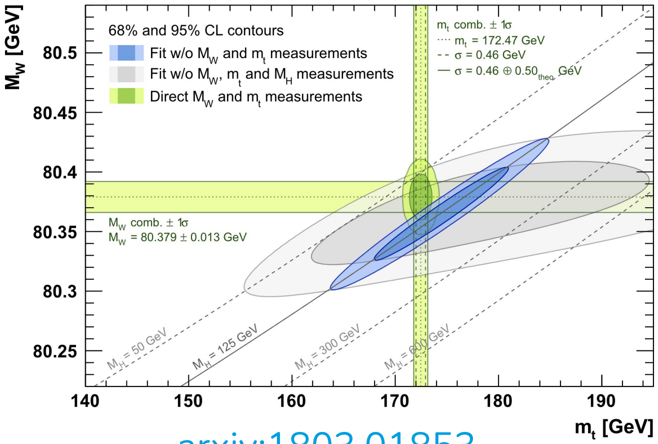
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Introduction

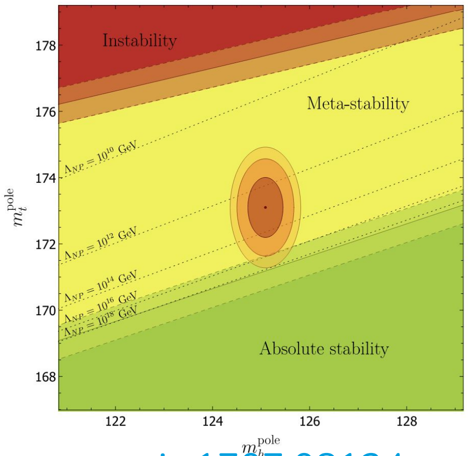
- Top quark mass *(m_t)* is a fundamental parameter of the Standard Model (SM)
  - Highest coupling to the Higgs boson

- m_t, m_W & m_H measurements can be compared to Electro-Weak (EW) fit predictions to check validity of SM

- EW vacuum is meta-stable in SM
  - Implications on the fate of the universe
  - If no new physics up to the Planck scale → stability of SM vacuum is dependent on m_H and m_t



arxiv:1803.01853



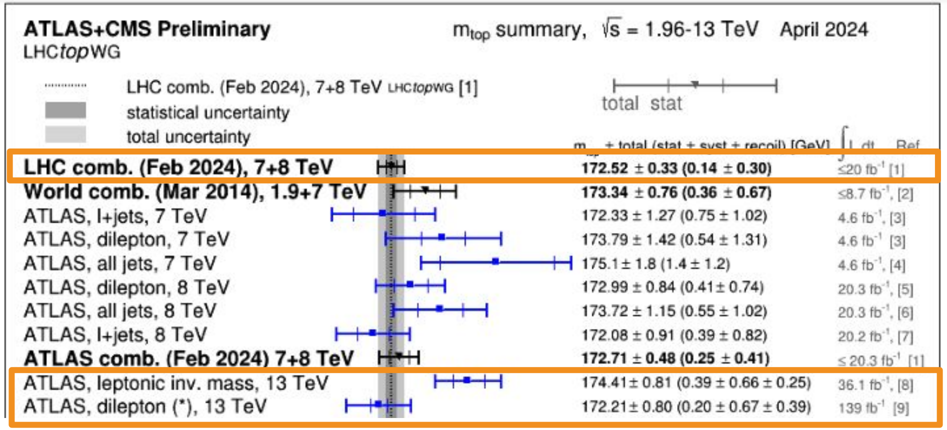
arxiv:1707.08124

Methods to measure the top-quark mass

ATLAS measures top-quark in various ways

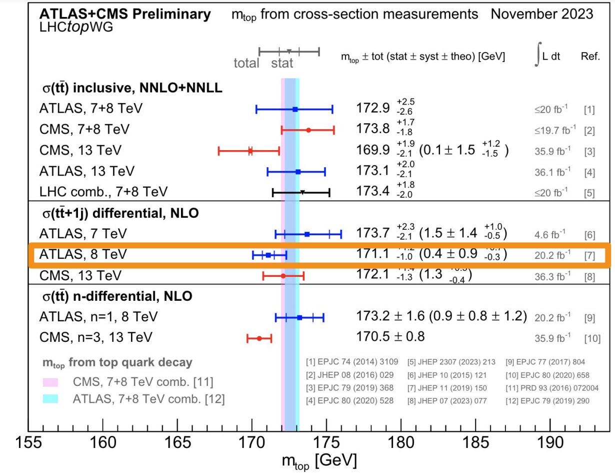
Direct measurement m_t^{MC}

- Observables reconstructed from top decay products
- Data compared to MC simulations with different input values of m_t



Indirect measurement m_t^{pole}

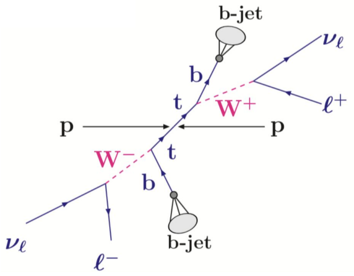
- From cross-sections (inclusive/differential)
- Measure observable(s) with a strong dependence on m_t with data unfolding
  - Compare to first principle calculations e.g. m^{pole}_t, *MS scheme*



Direct Measurements:

m^{MC}_{t} from $t\bar{t} \rightarrow$dilepton channel using the template method

(13 TeV , $\mathcal{L} = 139$ fb^{-1})

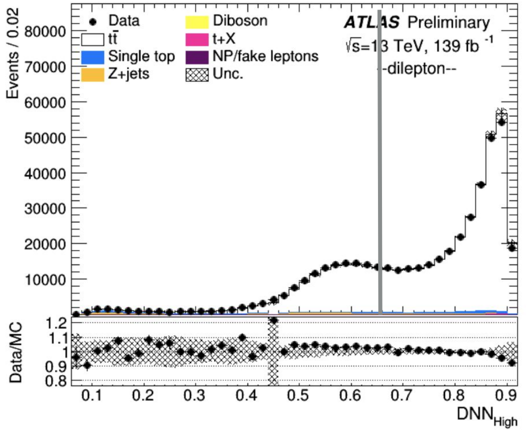


m^{MC}_t from template method

Selection and reconstruction

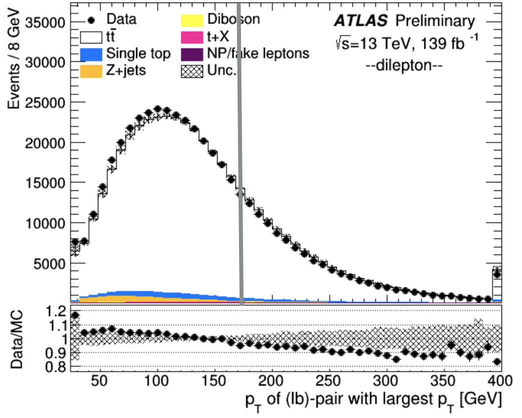
Reconstruction

- Correct matching: b-jet to lepton
- Use a DNN, which uses as input variables:
  - Kinematic variables of the individual objects
  - Kinematic variables and the invariant masses of all ℓb – pairs
  - Choose the permutation (out of 2) with the highest DNN value



Final Selection

- $DNN_{High} > 0.65$
  - Select the ℓb-pair with largest p_T
  - $p_{T,\ell b} > 160$ GeV
  - b-jet in that pair must be leading b-jet
- Reduced signal modelling and jet-related uncertainties

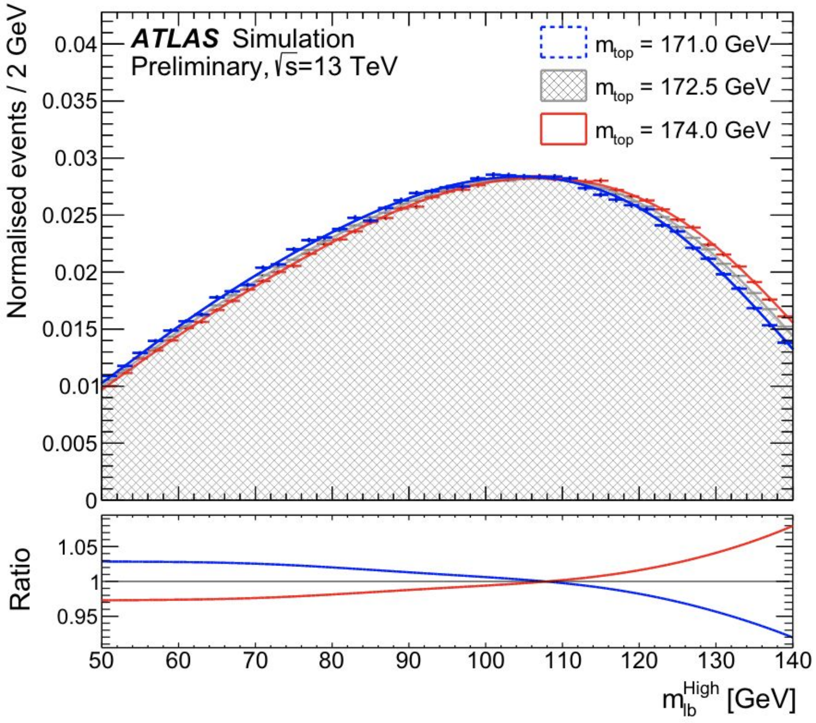


m^{MC}_t from template method

Mass extraction

- Unbinned maximum likelihood fit to data in range Between 50 and 140 GeV
  - Estimator: $m^{High}_{\ell b}$ invariant mass of selected ℓb-pair
  - Templates derived from ttbar and single-top samples

- Background fraction after the final selection: 0.6%
  - Not included in fit



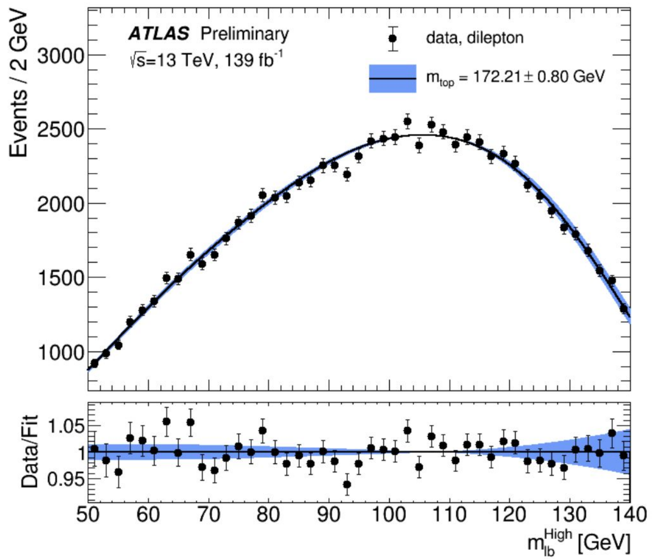
m^{MC}_t from template method

Results

m_t = 172.21 ± 0.20 (stat) ± 0.67 (syst) ± 0.39 (recoil) GeV

Dominant uncertainties come from the modelling:

- Matrix-element matching (0.40 GeV)
- Recoil Scheme (0.39 GeV)
- Jet Energy Scale (0.37 GeV)
- Colour reconnection (0.27 GeV)
- Data statistics (0.20 GeV)



Compatible with ATLAS and LHC combinations from Run-1
Similar precision to ATLAS measurement in same channel at 8 TeV

m^{MC}_t from template method

Recoil scheme

m_t = 172.21 ± 0.20 (stat) ± 0.67 (syst) ± 0.39 (recoil) GeV

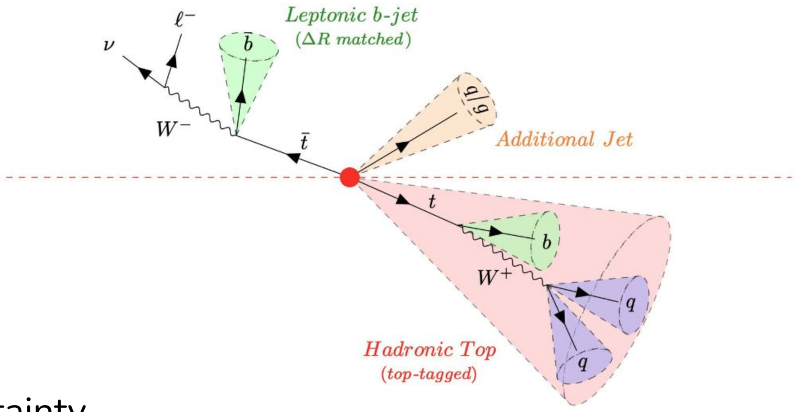
- Choice of recoil scheme impacts subsequent radiation off the *b*-quark after the first gluon emission

- Default option: Use b-quark as recoiler
- Latest option: Use top quark as recoiler

- Both vary the amount of :
  - Out-of-cone radiation and *W/b* momentum fraction
  - Translates into a shift of the inferred mtop.

- Recoil-to-top vs Recoil-to-*b* taken as an additional uncertainty.

- Current uncertainties probably overestimate the effect.
  - Hence treated separately in final results



Direct Measurements:

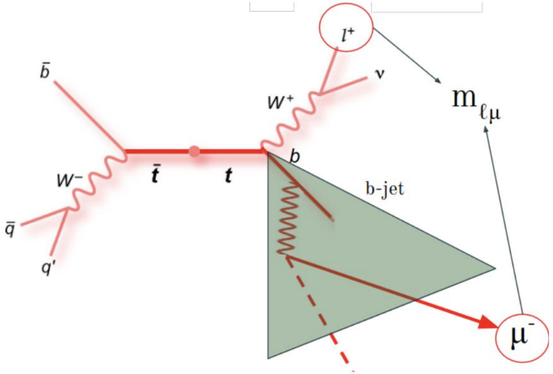
m^{MC}_{t} from $t\bar{t} \rightarrow \ell + \text{jets}$
using soft-muon tagging (SMT)

(13 TeV, $\mathcal{L} = 36.1\ \text{fb}^{-1}$)

JHEP06(2023)019

m^{MC}_t from soft muon tagging
Analysis strategy

Direct measurement of m^{MC}_t: from $t\bar{t} \to \ell$ + jets channel using experimental technique



Method to extract m^{MC}_t:

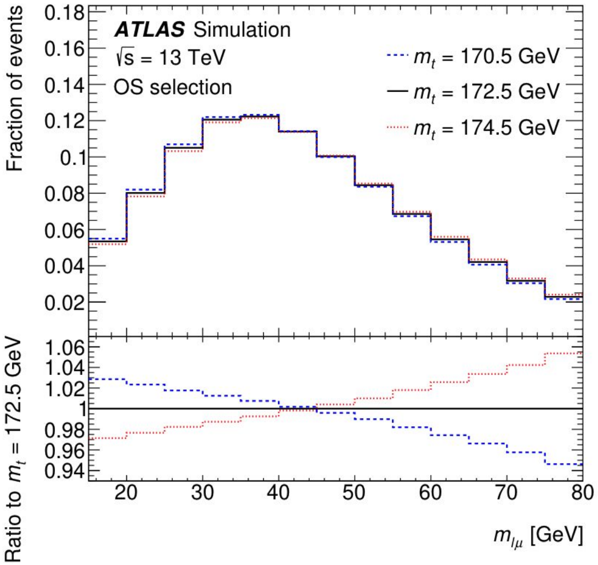
- Build $m_{l,\mu}$: semi-leptonic decay of top-quark
  - ℓ: prompt lepton from the W-boson decay
  - μ: soft muon from a b-hadron decay (SMT)

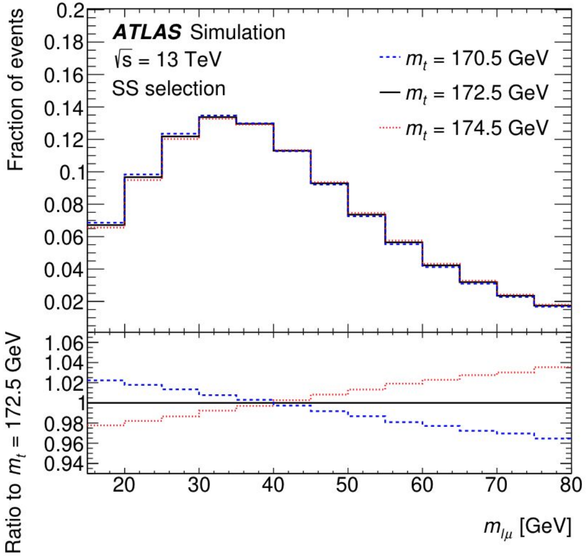
- Less sensitive to the jet related uncertainties
- Less sensitive to the modelling of top production
- Sensitive to the description of the b-fragmentation and b, c-hadron decays

JHEP06(2023)019

m^{MC}_t from soft muon tagging
Mass extraction

- Profiled Binned likelihood template fit in the sensitive 15-80 GeV region of $m_{l\mu}$
  - Simultaneously in OS and SS events
- Features 3 different masses for top
- Higher sensitivity of OS region to m_t well visible.





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m^{MC}_t from soft muon tagging

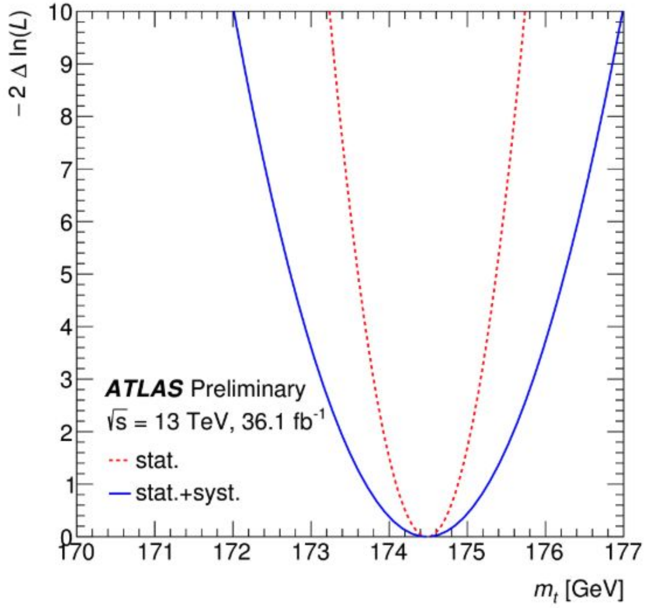
Results

m_t = 174.41 ± 0.39 (stat) ± 0.66 (syst) GeV ± 0.25 (recoil) GeV

Compatible with ATLAS combination at 2.2σ

Dominant uncertainties come from the modelling and stats:

- Branching ratio of *b/c* hadrons (0.40 GeV)
- Data statistics (0.39 GeV) [partial Run-2]
- Recoil Scheme (0.25 GeV) (not profiled)
- Initial State QCD radiation (0.23 GeV)
- *b*-quark fragmentation r_b (0.19 GeV)



Direct Measurements:

LHC top-quark mass combination in ATLAS/CMS

(7-8 TeV)

LHC top-quark mass combination in ATLAS/CMS Run-1

Methodology

Combination of 15 mass measurements performed by the ATLAS and CMS in different final state channels

Methodology:

- Use **B**est **L**inear **U**nbiased **E**stimator method (**BLUE**)

$$m_t = \sum w_i m^i_t, \text{ where } \sum w_i = 1$$

- Correlations between experiment → enter via systematic uncertainties
  - Must calculate/estimate the correlation between the measurements to get final covariance matrix.

Uncertainties

- b-JES is dominant
- Stats
- b-tagging
- ME generator
- JES.

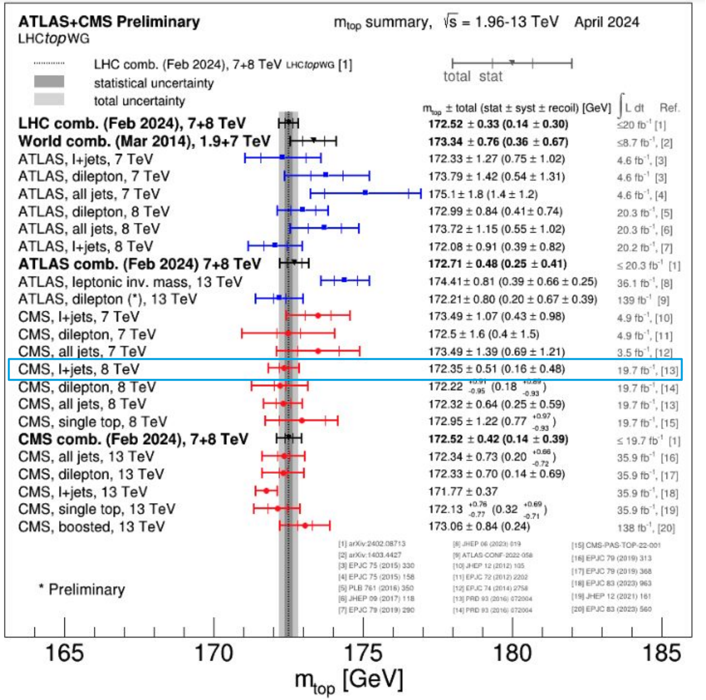
Uncertainty category	Uncertainty impact [GeV] LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
Hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

Top-quark mass combination ATLAS/CMS

Results

$$m_t = 172.52 \pm 0.14(\text{stat}) \pm 0.30(\text{syst})\ \text{GeV}$$

- Uncertainty of 0.33 GeV < 2 permil precision on top mass
- 31% improvement on most precise input
- Excellent compatibility, $\chi^2 = 7.5$; $p(\chi^2) = 0.91$
- Most precise measurement to date



Indirect Measurements:

m_t^{pole} using $t\bar{t}+1$-jet with the ATLAS experiment

(8 TeV, $\mathcal{L} = 20.2\ \text{fb}^{-1}$)

JHEP11(2019)150

m^{pole}_t from $t\bar{t}$+1jet production

Analysis strategy

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

Method to extract m^{pole}_t:

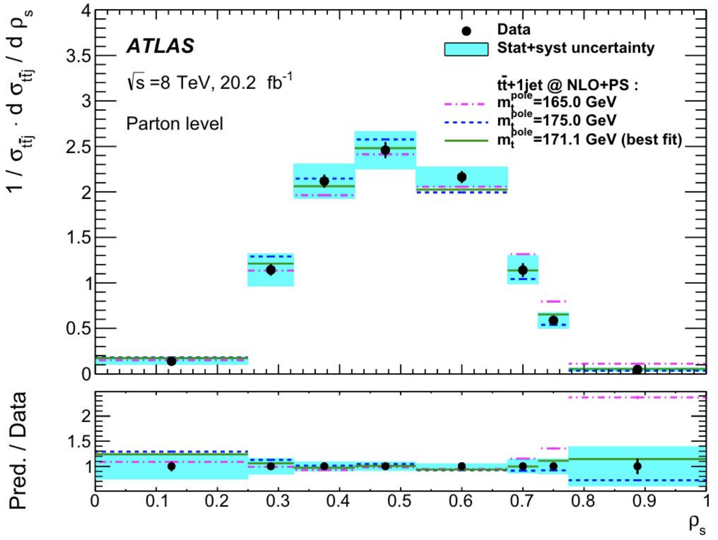
- Measure normalised $t\bar{t}$+1-jet differential distribution as a function of the invariant mass of the $t\bar{t}$+1-jet system ($m_{t\bar{t}+1\text{-}jet}$)
- Compare the unfolded distribution at parton level to NLO+PS $t\bar{t}$+1-jet calculations

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

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

- Measurement performed using unfolding at parton level.

- m^{pole}_t 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 :

$$\chi^2 = \sum_{i,j} \left[\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{data}} - \mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{NLO+PS}}(m_t^{\text{pole}})\right]_i \left[V^{-1}\right]_{ij} \left[\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{data}} - \mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{NLO+PS}}(m_t^{\text{pole}})\right]_j ,$$

m_t^{pole} from $t\bar{t}$+1jet 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)**

Dominant uncertainties:

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

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

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

$$\Delta m_t^{pole} = \,^{+1.2}_{-1.1}\ \text{GeV}$$

Summary

Summary

- m_t is a key parameter in the SM and BSM physics, it is known to high precision.

- LHC Run-1 combination in ATLAS/CMS the most precise result to date
  - Precision of 0.33 GeV

- Investigated several approaches:
  - Cross section measurements are used to perform an indirect measurement of m^{pole}_t
    - Precision of O(1) GeV
  - A template method is used to perform direct measurement of the top quark mass
    - Precision of 0.80 GeV
  - An experimental method is used to perform direct measurement of the top quark mass
    - Precision of 0.81 GeV

- All the methods provide precise measurements of the top-quark mass compatible with previous results

13 TeV analyses are ongoing: stay tuned for new results

Backup

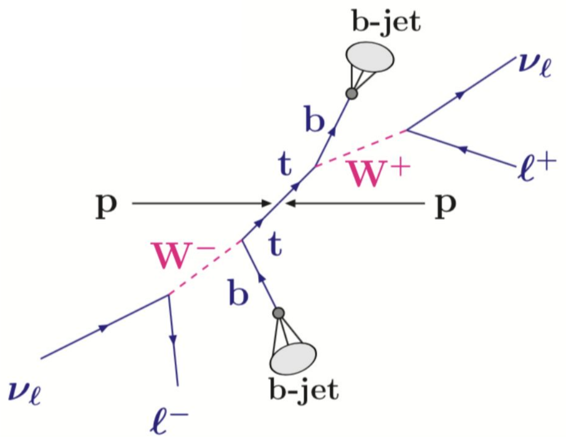
Direct Measurements:

$m^{MC}{}_{t}$ from ttbar →dilepton channel using the template method

m^{MC}_t from template method
Preselection

- Two reconstructed leptons with opposite charge with $p_T > 28$ GeV
- ≥ 2 jets with $p_T > 25$ GeV
- Exactly 2 *b*-jet, 70% efficiency WP (DL1r)
- Same flavour leptons: $m_{ll} < 80$ GeV or $m_{ll} > 100$ GeV, and $m_{ll} > 15$ GeV
  - Rejects Drell-Yan and Z+jets background events

Data	454960
$t\bar{t}$ signal	445000 ± 28000
Single-top-quark signal	14320 ± 890
Z+jets	10200 ± 4400
Diboson	420 ± 210
$t\bar{t}+V$, tWZ, tZq	1320 ± 200
$t\bar{t}+H$	440 ± 45
NP/fake leptons	760 ± 760
Signal+background	472000 ± 29000
Expected background fraction	0.028 ± 0.010
Data/(Signal + background)	0.963 ± 0.059



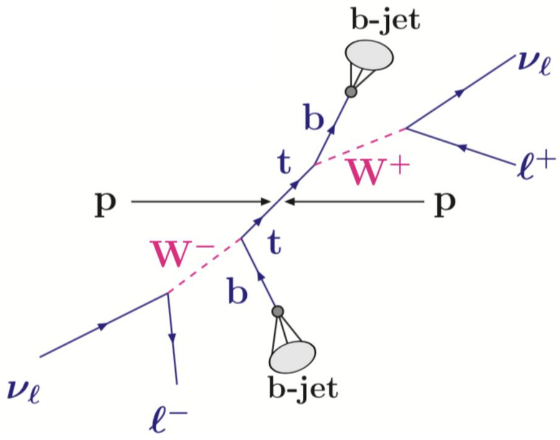
m^{MC}_t from template method
Event reconstruction

Signal events can be classified into 3 categories:

Unmatchable:
Either a reconstructed lepton or jet is not matched to its correct (generator) parton level partner.
Requirements are:
$\Delta R = 0.1$ for leptons (lepton from W-decay)
$\Delta R = 0.3$ for jets. (b-quarks)

Correctly matched:
Each lepton is assigned to its corresponding b-tagged jet

Incorrectly matched:
At least one reconstructed object is not correctly assigned



Reconstruction efficiency ≡ C/(C+I)

Signal purity ≡ C/(C+I+U)

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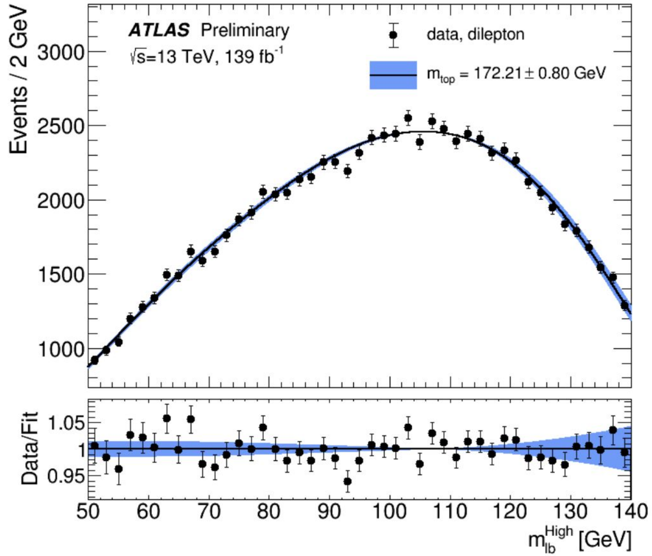
m^{MC}_t from template method

bb4l

m_t = 172.21 ± 0.20 (stat) ± 0.67 (syst) ± 0.39 (recoil) GeV

Dominant uncertainties come from the modelling:

- Matrix-element matching (0.40 GeV)
- Recoil Scheme (0.39 GeV)
- Jet Energy Scale (0.37 GeV)
- Colour reconnection (0.27 GeV)
- Data statistics (0.20 GeV)



Check: Impact of off-shell and non-resonants effects on m_t has been estimated using the bb4l generator in Powheg:

Δm_t = -0.23 ± 0.14 GeV < modelling uncertainties

Compatible with ATLAS and LHC combinations from Run-1

Similar precision to ATLAS measurement in same channel at 8 TeV

m_t^{MC} from template method

Systematic uncertainties

	m_{top} [GeV]
Result	172.21
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.40 ± 0.06
Parton shower and hadronisation	0.05 ± 0.05
Initial- and final-state QCD radiation	0.17 ± 0.02
Underlying event	0.02 ± 0.10
Colour reconnection	0.27 ± 0.07
Parton distribution function	0.03 ± 0.00
Single top modelling	0.01 ± 0.01
Background normalisation	0.03 ± 0.02
Jet energy scale	0.37 ± 0.02
b-jet energy scale	0.12 ± 0.02
Jet energy resolution	0.13 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.11 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.39 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.80 ± 0.06

The top quark mass is measured in dileptonic channel using lepton/b-jet invariant mass with a total uncertainty of 0.80 GeV.

Dominant uncertainties come from the modelling:

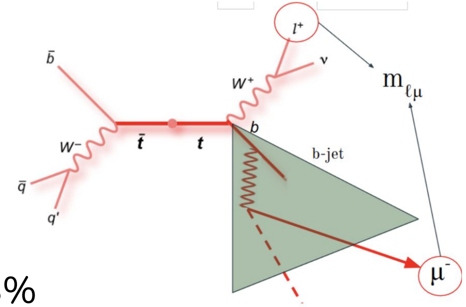
- Matrix-element matching (0.40 GeV)
- Recoil Scheme (0.39 GeV)
- Jet Energy Scale (0.37 GeV)
- Corlour reconnection (0.27 GeV)
- Data statistics (0.20 GeV)

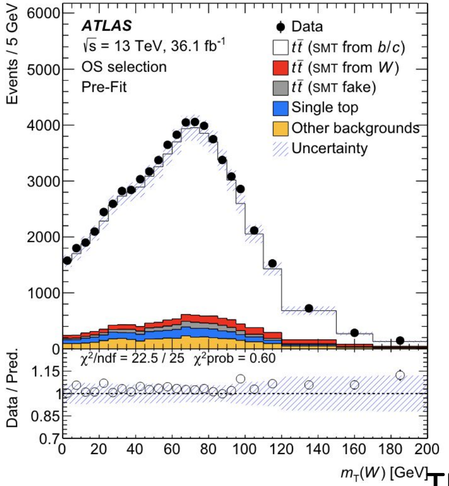
Direct Measurements:

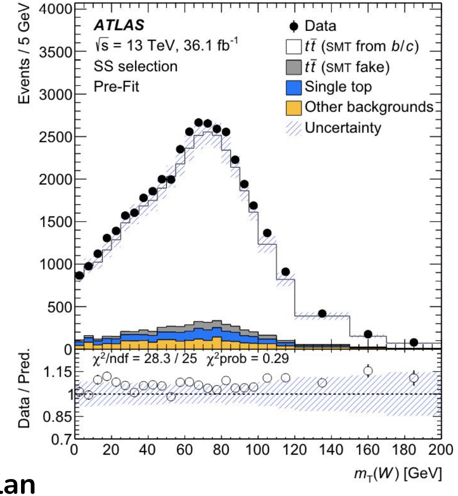
m^{MC}_{t} from ttbar →l + jets using soft-muon tagging (SMT)

m_t^{MC} from soft muon tagging
Event Selection and reconstruction

- Exactly 1 isolated e or μ *(associated to W-boson decay)*
- Requirement in E^{miss} and $M_T(W)$ to infer presence of neutrino
- ≥ 4 jets
- ≥ 1 b-jet, 77% efficiency WP
- ≥ 1 SMT jet (i.e. μ with p_T > 8 GeV found within ΔR < 0.4 of a jet)
- Event yields after selection: 67k (SS) and 42k (OS). signal purity: 86% and 88%







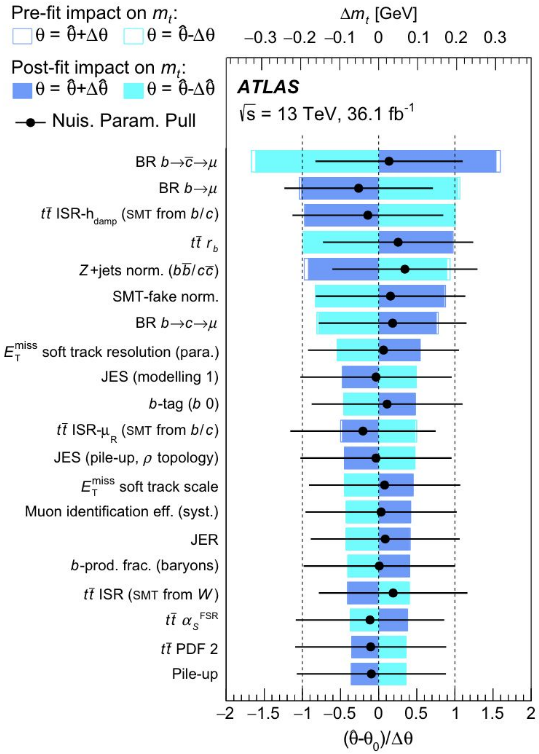
m^{MC}_t from soft muon tagging

OS and SS

- Sample split into OS (mostly direct $b \to \mu X$ decays) vs SS (mostly sequential $b \to cX' \to \mu X''$)
  - OS: 83% same top, 10% different top, 7% unmatched to b from top (mostly from $t \to W \to cs$)
  - SS: 57% same top, 41% different top, 2% unmatched

m^{MC}_t from soft muon tagging

Fit results



No strong pulls or constraints are observed in the ranking plots for the main uncertainties

Numerous checks performed showing fit stability

- BR b→cc→mu
- BR b→mu
- Initial State QCD radiation
- r_b : impacts fragmentation

m_t^{MC} from soft muon tagging

Systematic uncertainties

Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Statistical and datasets		
Data statistics	0.39	
Signal and background model statistics	0.17	
Luminosity	< 0.01	±0.01
Pile-up	0.07	±0.03
Modelling of signal processes		
Monte Carlo event generator	0.04	±0.06
b, c-hadron production fractions	0.11	±0.01
b, c-hadron decay BRs	0.40	±0.01
b-quark fragmentation r_b	0.19	±0.06
Parton shower α_S^{FSR}	0.07	±0.04
Parton shower and hadronisation model	0.06	±0.07
Initial-state QCD radiation	0.23	±0.08
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.07	±0.01
Modelling of background processes		
Soft muon fake	0.16	±0.03
Multijet	0.07	±0.02
Single top	0.01	±0.01
W/Z+jets	0.17	±0.01
Detector response		
Leptons	0.12	±0.01
Jet energy scale	0.13	±0.02
Soft muon jet p_T calibration	< 0.01	±0.01
Jet energy resolution	0.08	±0.07
b-tagging	0.10	±0.01
Missing transverse momentum	0.15	±0.01
Total stat. and syst. uncertainties (excluding recoil)	0.77	±0.03
Recoil uncertainty	0.25	
Total uncertainty	0.81	

The top quark mass is measured using a leptonic invariant mass involving SMT muons with a total uncertainty of 0.81 GeV.

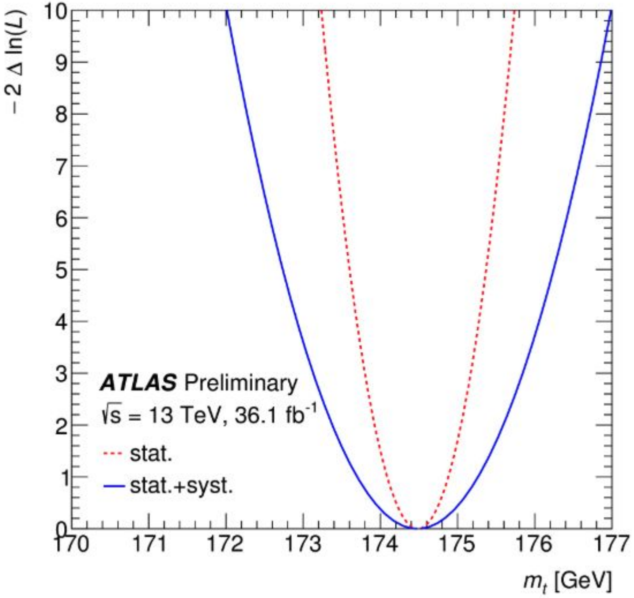
Dominant uncertainties come from the modelling:

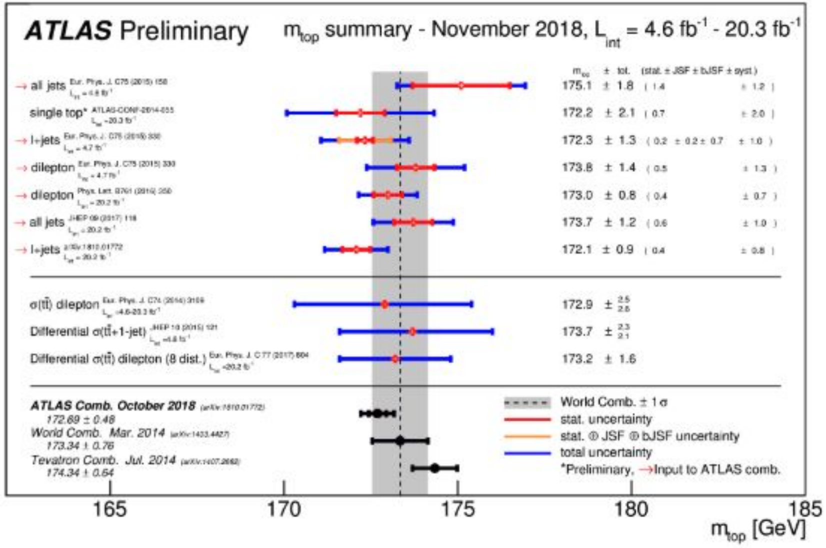
- Branching ratio of b/c hadrons (0.40 GeV)
- Data statistics (0.39 GeV) [partial Run-2]
- Recoil Scheme (0.25 GeV) (not profiled)
- Initial State QCD radiation (0.23 GeV)
- b-quark fragmentation r_b (0.19 GeV)

Background modelling and calibration of jet energies is subdominant

m^{MC}_t from soft muon tagging

Results





m_t = 174.41 ± 0.39 (stat) ± 0.66 (syst) GeV ± 0.25 (recoil)

Compatible with ATLAS combination at 2.2sigma
Precise measurement, competitive with "standard" direct techniques!

Direct Measurements:

LHC top-quark mass combination in
ATLAS/CMS
(7-8 TeV)

Top-quark mass combination ATLAS/CMS
Correlation strength

Between ATLAS & CMS: estimate

- Uncorrelated: $\rho = 0$ [-0.25, 0.25]
- Partially correlated: $\rho = 0.5$ [0.25, 0.75]
- Strongly correlated: $\rho = 0.85$ [0.75, 1.0]

Scan around nominal value to test stability of the guess

Top-quark mass combination ATLAS/CMS

Systematic uncertainties and correlations

b-JES/g-JES : strong dependence on MC

Leptons/Trigger: from data

b-tagging : relies on MC

Modelling uncertainties : almost all correlated

Uncertainty category	ρ	Scan range	$\Delta m_t/2$ [MeV]	$\Delta\sigma_{m_t}/2$ [MeV]
JES 1	0	—	—	—
JES 2	0	[−0.25, +0.25]	8	7
JES 3	0.5	[+0.25, +0.75]	1	<1
b-JES	0.85	[+0.5, +1]	26	5
g-JES	0.85	[+0.5, +1]	2	<1
l-JES	0	[−0.25, +0.25]	1	<1
CMS JES 1	—	—	—	—
JER	0	[−0.25, +0.25]	5	1
Leptons	0	[−0.25, +0.25]	2	2
b tagging	0.5	[+0.25, +0.75]	1	1
p_T^{miss}	0	[−0.25, +0.25]	<1	<1
Pileup	0.85	[+0.5, +1]	2	<1
Trigger	0	[−0.25, +0.25]	<1	<1
ME generator	0.5	[+0.25, +0.75]	<1	4
QCD radiation	0.5	[+0.25, +0.75]	7	1
Hadronization	0.5	[+0.25, +0.75]	1	<1
CMS b hadron $\mathcal{B}$	—	—	—	—
Color reconnection	0.5	[+0.25, +0.75]	3	1
Underlying event	0.5	[+0.25, +0.75]	1	<1
PDF	0.85	[+0.5, +1]	1	<1
CMS top quark p_T	—	—	—	—
Background (data)	0	[−0.25, +0.25]	8	2
Background (MC)	0.85	[+0.5, +1]	2	<1
Method	0	—	—	—
Other	0	—	—	—

Vary in range → shift in central value of m_{top}

Mild dependence on b-JES correlations

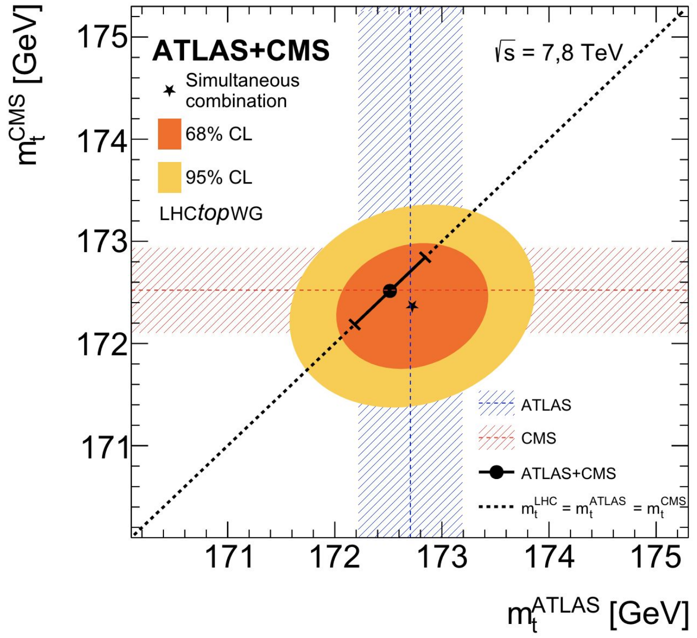
Top-quark mass combination ATLAS/CMS

Cross-check

Final cross-check: compare the various fit scenarios

- ATLAS-only combination
- CMS-only combination
- simultaneous combination but with 2 mass parameters
- simultaneous combination with 1 mass parameter = LHC combination

All in excellent agreement with each other



Top-quark mass combination ATLAS/CMS

Important Analyses

	ATLAS						CMS									
	2011 (7 TeV)			2012 (8 TeV)			2011 (7 TeV)			2012 (8 TeV)						
	dil	lj	aj	dil	lj	aj	dil	lj	aj	dil	lj	aj	t	J/ψ	vtx	
Pull	+0.93	−0.15	+1.43	+0.61	−0.51	+1.09	−0.01	+0.96	+0.71	−0.33	−0.47	−0.37	+0.38	+0.31	+1.08	
Weight	−0.02	+0.07	+0.00	+0.16	+0.17	+0.03	−0.08	−0.01	+0.03	+0.12	+0.34	+0.12	−0.03	+0.01	+0.08	

ATLAS:
lepton + jets (8TeV)
dilepton (8TeV)

CMS:
lepton + jets (8TeV)

Indirect Measurements:

m_t^{pole} using $t\bar{t}$+1-jet with the ATLAS experiment

(8 TeV)

m_t^{pole} from $t\bar{t}$+1jet production
Event Selection and reconstruction

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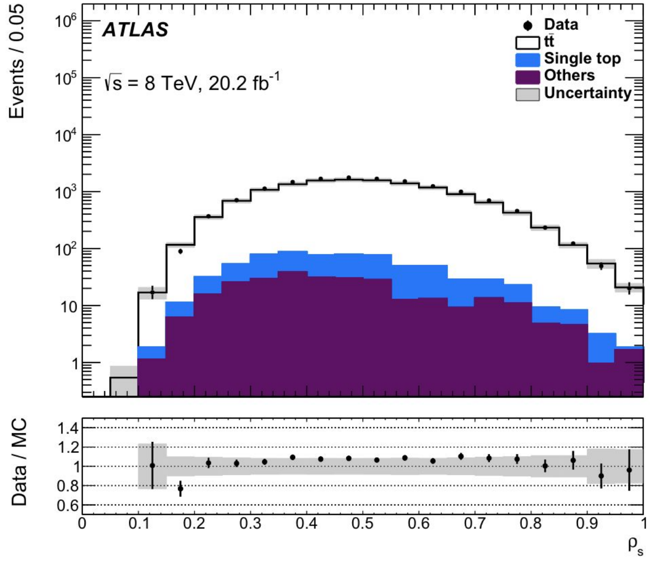
- Exactly 1 reconstructed e or μ with p_T > 25 GeV.
- >= 5 jets (anti$_{kt}$ jet reconstruction algorithm).
- The extra jet is the leading jet with p_T > 50 GeV and $|\eta|$ < 2.5.
  - Not used in the $t\bar{t}$ reconstruction.

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



e+jets channel: signal purity of ~ 94%
μ+jets channel: signal purity of ~ 95%

m^{pole}_t from $t\bar{t}$+1jet production

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Reconstruction

Hadronically decaying W-boson

Collecting all pairs of jets that are not b-tagged

- $0.9 < m_W/m_{ij} < 1.25$
- $\min\left(p_T^i,\ p_T^j\right) \cdot \Delta R_{ij} < 90$ GeV

Leptonically decaying W-boson

Neutrino inferred by MET > 30 GeV and M_T(W) > 30 GeV

W-boson: lepton + up to 2 neutrinos

Top quark candidates

Combine all the hadronic and leptonic W-boson candidates with the two b-tagged jets

Select one that minimised the following

$$\frac{\left|m_{t_{\text{lept}}} - m_{t_{\text{had}}}\right|}{m_{t_{\text{lept}}} + m_{t_{\text{had}}}}$$

$$m_{t_{\text{lept}}}/m_{t_{\text{had}}} > 0.9.$$

Relation between $\overline{\text{MS}}$ 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 tt+ 1-jet cross section used to extract the mass in both schemes.

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

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

- When converting mt(mt) to m pole t the obtained value is ≈ 170.9 GeV.
  - Good agreement with the direct extraction of m_t^{pole} .

m^{pole}_t from $t\bar{t}$+1jet production
Unfolding methodology

$$\mathcal{R}^{t\bar{t}+1\text{-jet}}(\rho_s) = \left[\mathcal{M}^{-1} \otimes \mathcal{R}^{\text{det}}(\rho_s)\right] \cdot f(\rho_s) \cdot f^{\text{ph.sp.}}\left(\rho_s, \mathcal{R}^{t\bar{t}+1\text{ jet}}_{\text{ACC}}\right).$$

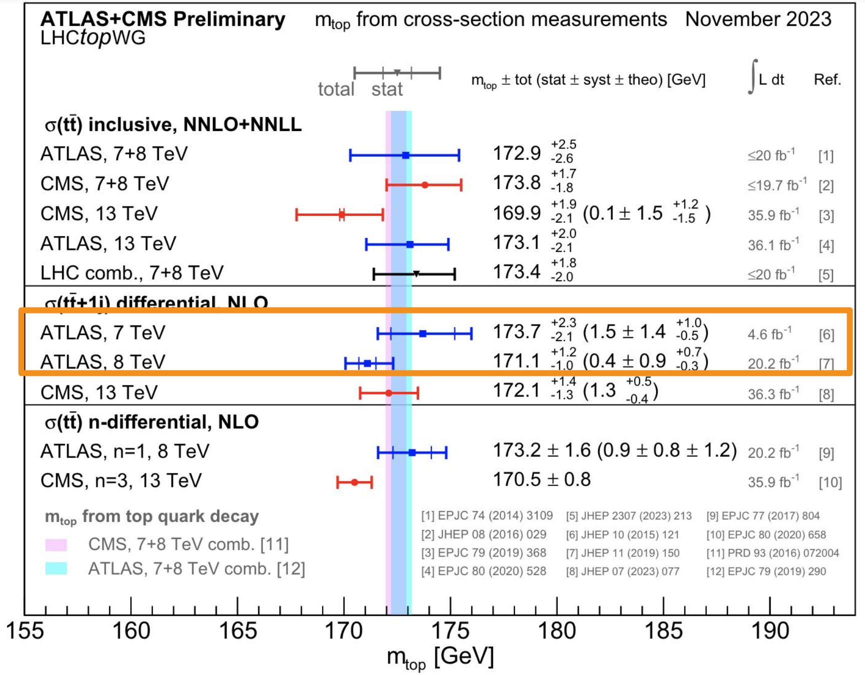
- R data distribution is corrected for the following in order to get the distribution at parton level and compare with **fixed order calculation.**
  - Detector
  - Hadronization
  - gluon radiation
  - top-quark decay effects

.

m^{pole}_t from $t\bar{t}$+1jet production
Summary

- m^{pole}_t result obtained from data unfolded to parton level is compatible with previous measurements

- Statistical and systematic uncertainties reduced by a factor 2 w.r.t 7 TeV measurement JHEP10(2015)121
  - Due to large reduction in JES systematic
    - More stats → finer binning
    - larger sensitivity of $\mathcal{R}$ to top-quark pole mass
  - Better knowledge of the detector

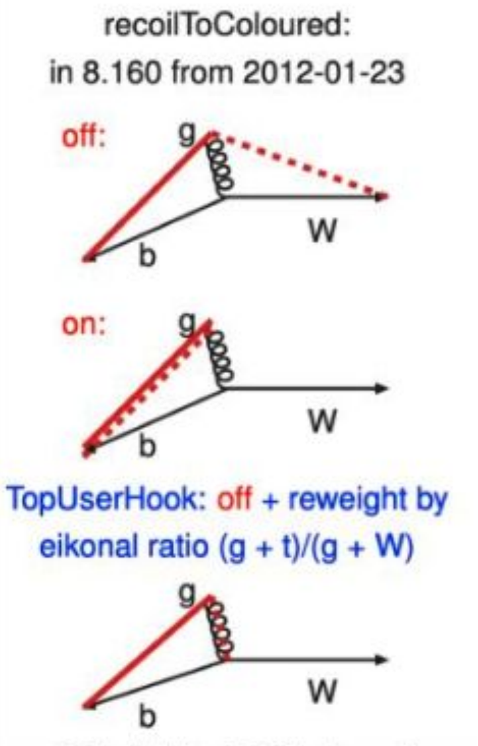


Other

Top mass SMT: recoil in PS

A new **uncertainty due to gluon emission in t→Wb.** Various schemes:

- Powheg+Pythia8 (default):
  - **recoil-to-colour=ON scheme**
  - where any **gluon radiation after the first emission recoils** against the **b-quark**.
- Pythia (previous version from Run-1):
  - **recoil-to-colour=OFF** scheme, where the **W-boson** was the **recoiler.**
- A recent third option **(Recoil-to-Top)** allows the **top** to be the **recoiler**.
- All these schemes vary the amount of :
  - out-of-cone radiation and W/b momentum fraction
  - translates into a shift of the inferred mtop.
- Following previous recommendations, ATLAS has added **recoil-to-top** vs **recoil-to-colour=ON** as an additional uncertainty.
- No dedicated tuning of the recoil-to-top has been performed yet. Current uncertainties probably overestimate the effect.



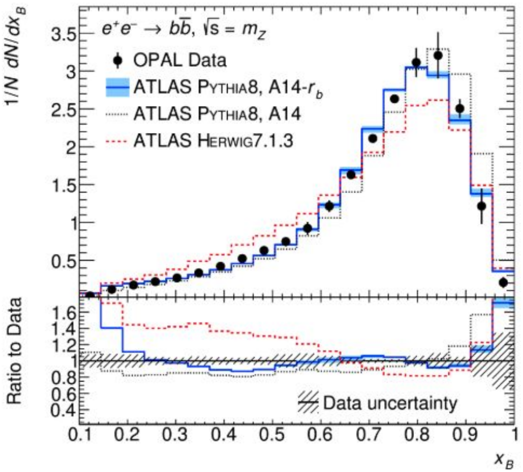
(Sketch by T. Sjostrand)

Modelling of heavy-quark fragmentation

- A need to describe the **momentum transfer between b-quark and b-hadron**:
  - **Free parameters are tuned to data (e+e - colliders)**.
- Pythia 8 uses the **Lund-Bowler parametrization**:

$$f(z) = \frac{1}{z^{1+br_b m_b^2}}(1-z)^a \exp(-bm_T^2/z)$$

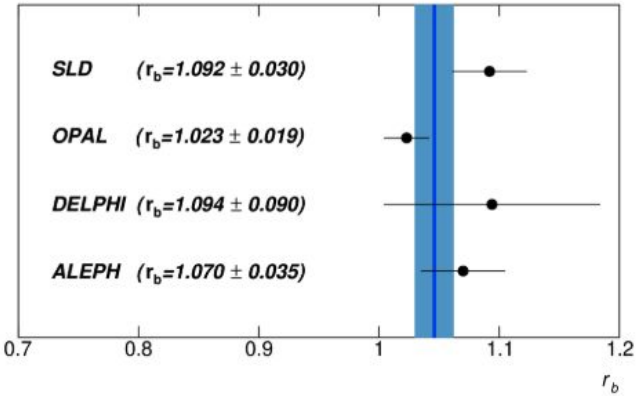
$$m_T = \sqrt{m_B^2 + p_T^2}$$



- ***z***- fraction of longitudinal energy carried by the b-hadron relative to b-quark.
- ***a***, ***b*** and ***r_b*** are the free parameters
  - ***r_b*** is specific to **b-fragmentation**.
- Nominal **ATLAS A14** description of the b-quark fragmentation is **improved** by **fitting** for the ***r_b*** parameter using data from **LEP and SLC**.
- **Best *r_b*** value extracted from a □^{2} fit to:
  - $x_B = 2p_B\, p_Z / m^2_Z$
  - **The relative B-hadron energy to the Z-boson mass.**

Modelling of heavy-quark fragmentation

- The □^{2} curves of the **four experiments combined in a single □^{2}** one



Experiment	r_b	χ^2/ndf
ALEPH	1.070 ± 0.035	21/18
DELPHI	1.094 ± 0.030	73/8
OPAL	1.023 ± 0.019	18/19
SLD	1.092 ± 0.018	58/21

Best fit: $\mathbf{r_b = 1.05 \pm 0.02}$

Modelling hadron production and decays

- The **production fractions** of weakly decaying **b- and c-hadrons** have been rescaled to the **PDG values**.

Hadron	PDG	POWHEG+PYTHIA8	Scale Factor
B^0	0.404 ± 0.006	0.429	0.941 ± 0.014
B^+	0.404 ± 0.006	0.429	0.942 ± 0.014
B_s^0	0.103 ± 0.005	0.095	1.088 ± 0.052
b-baryon	0.088 ± 0.012	0.047	1.87 ± 0.26
D^+	0.226 ± 0.008	0.290	0.780 ± 0.027
D^0	0.564 ± 0.015	0.553	1.020 ± 0.027
D_s^0	0.080 ± 0.005	0.093	0.857 ± 0.054
c-baryon	0.109 ± 0.009	0.038	2.90 ± 0.24

- The **branching ratios** of the **b- and c hadron decays** containing a soft muon are also adjusted.

Hadronic Decay Mode	PDG	POWHEG PYTHIA8	Scale Factor
$b \to \mu$	$0.1095\ ^{+0.0029}_{-0.0025}$	0.106	$1.032\ ^{+0.0027}_{-0.0023}$
$b \to \tau$	0.0042 ± 0.0004	0.0064	0.661 ± 0.062
$b \to c \to \mu$	0.0802 ± 0.0019	0.085	0.946 ± 0.022
$b \to \bar{c} \to \mu$	0.016 ± 0.003	0.018	0.89 ± 0.17
$c \to \mu$	0.082 ± 0.005	0.084	0.976 ± 0.059