

Measurements of the top quark mass with the ATLAS detector

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on behalf of the ATLAS Collaboration

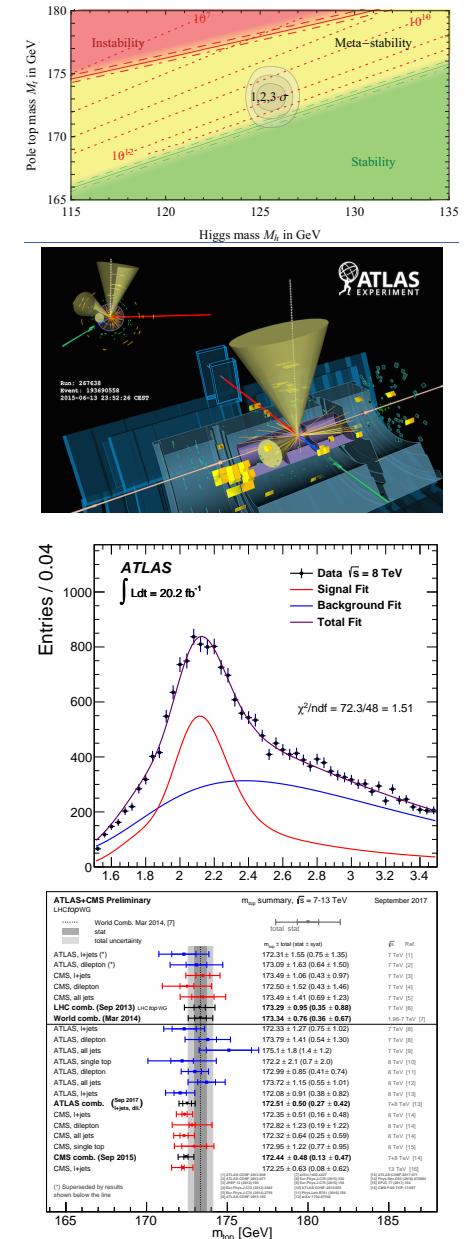
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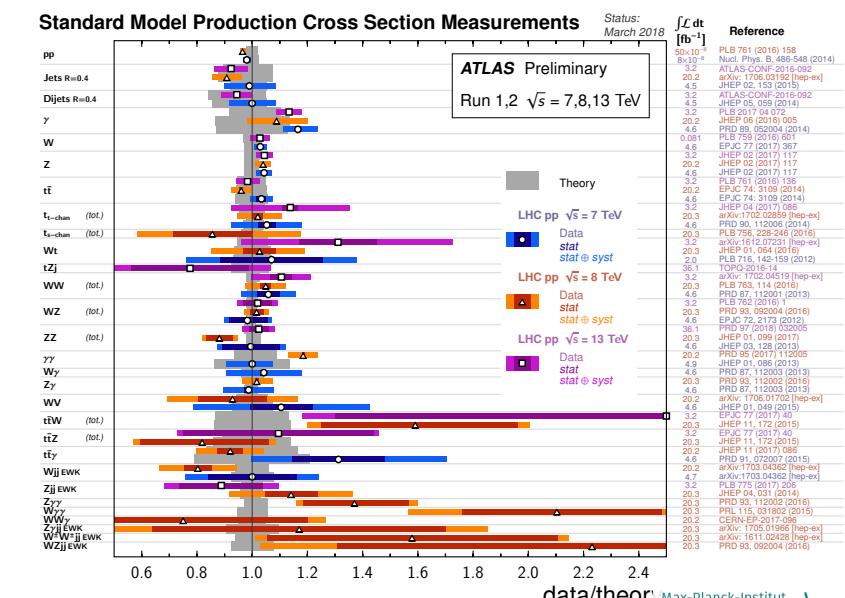
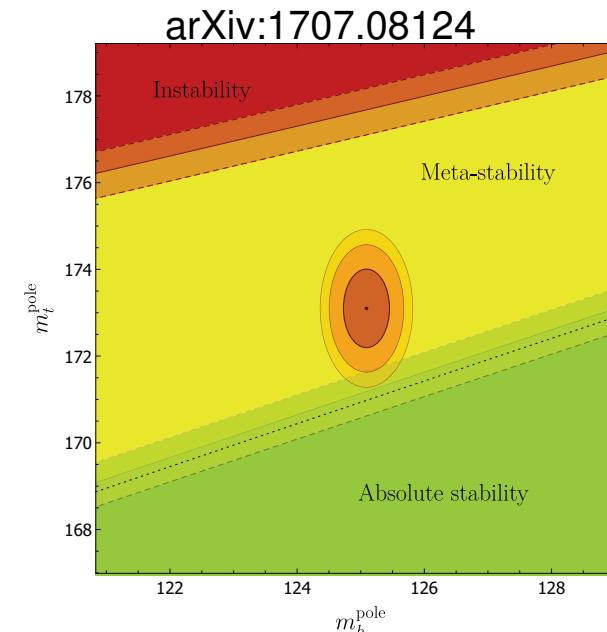
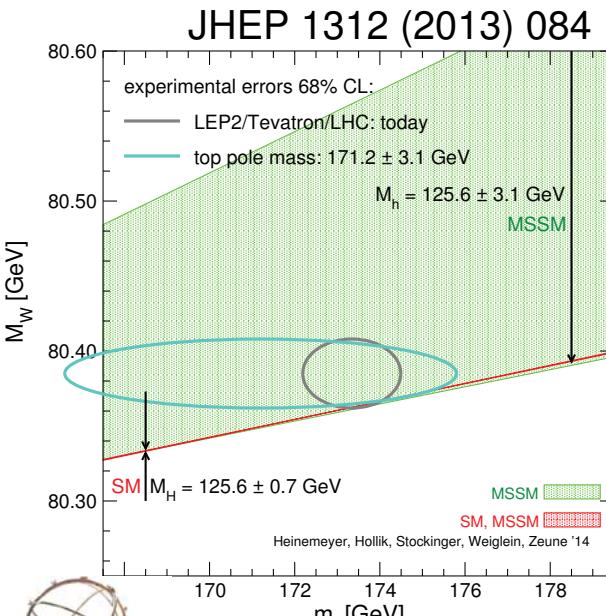
Overview

- ▶ Introduction
- ▶ Top-quark production
- ▶ Direct and indirect top-quark mass measurements
- ▶ Direct top-quark mass measurements in ATLAS
- ▶ Indirect top-quark mass measurements in ATLAS
- ▶ Conclusions



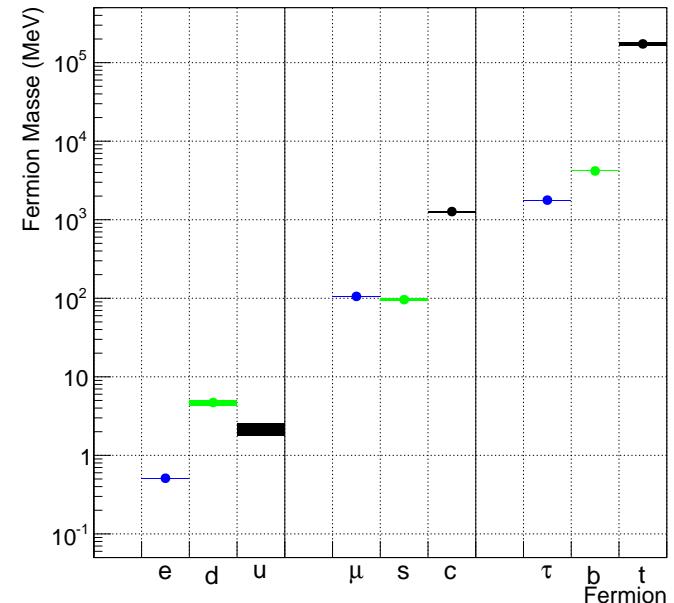
Introduction

- The top-quark mass, m_{top} , is a fundamental parameter of the Standard Model (SM)
- Precise determinations of the SM parameters allow to challenge consistency tests of the SM and to look for signs of new physics beyond the SM (BSM)
- Plots show: (left) the W mass, m_W , and top-quark pole mass, $m_{\text{top}}^{\text{pole}}$, with 1σ uncertainties in comparison with the SM and the MSSM prediction; (central) $m_{\text{top}}^{\text{pole}}/m_H$, mass of the Higgs, plane confronted with the SM vacuum expectations. Ellipses show 68%, 95% and 99% contours based on the experimental uncertainties on $m_{\text{top}}^{\text{pole}}$ and m_H ; (right) ATLAS results on cross-section measurements compared and still in agreement with the SM predictions. Not all measurements are statistically significant

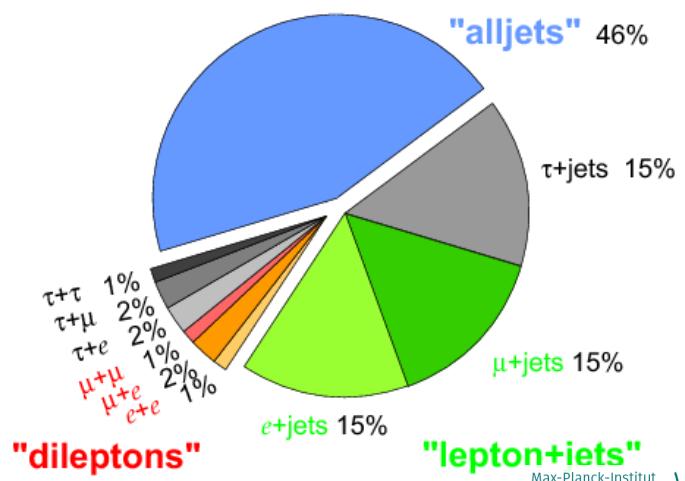


Top quark production

- ▶ The top quark is the heaviest known elementary particle, $m_{\text{top}} \approx 173 \text{ GeV}$ (left top plot)
- ▶ It decays before hadronization (lifetime $\tau = \sim 5 \times 10^{-25} \text{ s}$)
- ▶ Main top decay: $t \rightarrow W b$
- ▶ Leading $t\bar{t}$ -production process final states divided in three classes:
 - All-jets (46.2%):
 $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}' b q'' \bar{q}''' b$
 - Lepton+jets (43.5%):
 $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}' b \ell \bar{\nu}_\ell \bar{b} + \bar{\ell} \nu_\ell b q \bar{q}' \bar{b}$
 - Dilepton (10.3%):
 $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow \bar{\ell} \nu_\ell b \ell' \bar{\nu}_{\ell'} \bar{b}$
- ▶ LHC is a top quark factory
 - $\sigma_{t\bar{t}}(14.0 \text{ TeV}) = 800 \text{ pb}$, 2 $t\bar{t}$ events per second
- ▶ Total cross section for $t\bar{t}$ -production about a factor of 100 larger at LHC than at Tevatron



Top Pair Branching Fractions



Top-quark mass measurements

- ▶ Different definitions of m_{top} :
 - The top-quark Monte Carlo (MC) mass, $m_{\text{top}}^{\text{MC}}$, parameter measured from comparison to MC events with top-quark decay products
 - The top-quark pole mass, $m_{\text{top}}^{\text{pole}}$, parameter is the classic rest mass entering the top propagator
 - The running top-quark mass, \overline{MS} mass, parameter defined in a low-scale short distance scheme
- ▶ Typical $m_{\text{top}}^{\text{MC}}$ (or m_{top}) analyses reconstruct top quark candidates in data and MC often using kinematic fits and likelihood fits based on templates, in one or more parameters
- ▶ Though m_{top} (direct measurement) $\neq m_{\text{top}}^{\text{pole}}$ (indirect measurement)
- ▶ “The uncertainty on the translation from the $m_{\text{top}}^{\text{MC}}$ definition to a theoretically well defined short distance mass definition at low scale is currently estimated to be of the order of 1 GeV” (arxiv:1405.4781, arXiv:1408.6080, Nucl. Phys. Proc. Suppl. 185 (2008):220-226)
- ▶ Although it may be much smaller, perhaps < 100 MeV (arXiv:1712.02796, arXiv:1608.01318)
- ▶ Cross-section based methods measure a theoretically well defined mass e.g. the $m_{\text{top}}^{\text{pole}}$, though with not competitive precision $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 5\% \rightarrow \Delta m_{\text{top}}/m_{\text{top}} \sim 1\%$
- ▶ In the following the latest m_{top} and $m_{\text{top}}^{\text{pole}}$ ATLAS results will be presented

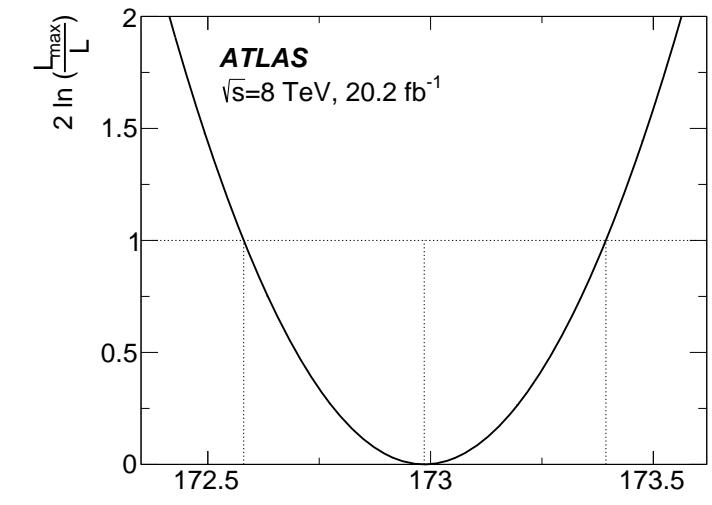
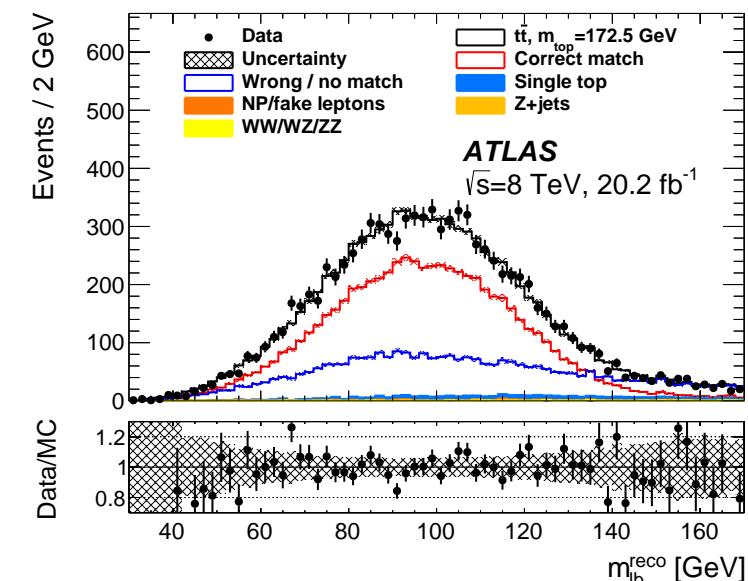


Dilepton m_{top} measurement at 8 TeV

- ▶ Direct: m_{top} measurement from $t\bar{t}$ dilepton channel
- ▶ After a preselection, keep events with two central ($|\eta| < 2.5$) b-tagged jets (b-jet) and two oppositely charged central leptons (ℓ) ‘
- ▶ The combination with the lowest average invariant mass of the two ℓ -b-jet pairs, $m_{\ell b}^{\text{reco}}$, with $30 \text{ GeV} < m_{\ell b}^{\text{reco}} < 170 \text{ GeV}$ is retained
- ▶ A cut on the average p_T of the two ℓ -b-jet pairs $p_{T\ell b} > 120 \text{ GeV}$ is applied to optimize the final m_{top} uncertainty
- ▶ The analysis uses a template fit to $m_{\ell b}^{\text{reco}}$
- ▶ An unbinned likelihood maximization gives the m_{top} value that best describes the data
- ▶ $m_{top} = 172.99 \pm 0.41 \text{ (stat)} \pm 0.74 \text{ (syst)} \text{ GeV}$
- ▶ Biggest systematic uncertainties: jet energy scale (JES) and relative b-to-light-jet energy scale (bJES)
- ▶ Most precise result in this decay channel to date

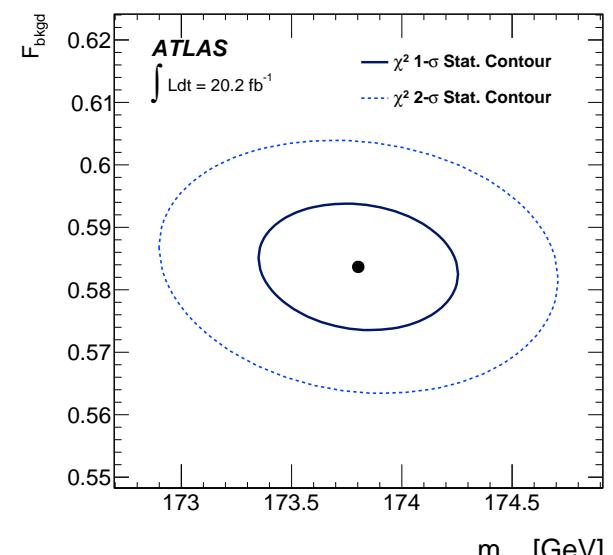
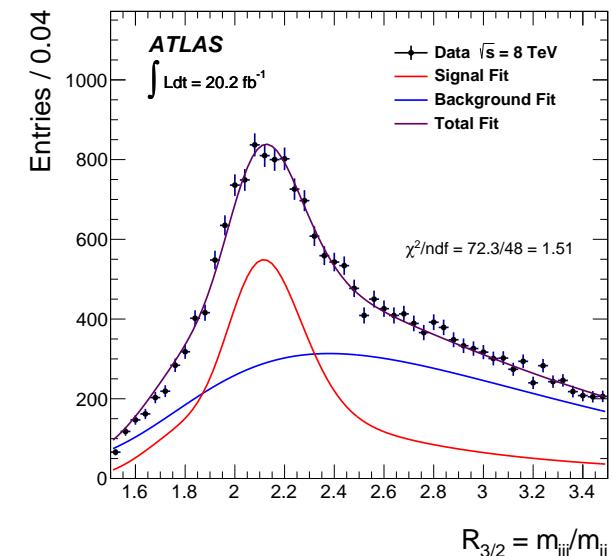
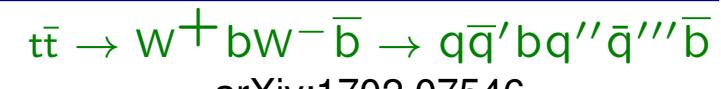
$t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow \ell^\pm \ell^\pm \nu \bar{\nu} b \bar{b}$

Phys. Lett. B 761 (2016) 350-371



All-jets m_{top} measurement at 8 TeV

- ▶ Direct: m_{top} measurement from $t\bar{t}$ all-jets channel
- ▶ Challenging measurement because of the large multi-jets background
- ▶ Basic selection: no leptons, ≥ 6 central ($|\eta| < 2.5$) jets two of them b-jets, $E_T^{\text{Miss}} < 60$ GeV, topological cuts applied to reduce background
- ▶ Jet assignment made by χ^2 fit to the $t\bar{t}$ system
- ▶ A data-driven method is used to determine the large multi-jets background with regions defined by number of b-jet and proximity of W, b pairs
- ▶ m_{top} measurement extracted using a template fit to the ratio of the three-jet to the dijet mass, $R_{3/2}$, with a binned minimum- χ^2 approach
- ▶ $m_{\text{top}} = 173.72 \pm 0.55 \text{ (stat)} \pm 1.01 \text{ (syst)} \text{ GeV}$
- ▶ Biggest systematic uncertainties: hadronisation modeling, JES, and bJES
- ▶ Measurement $\sim 40\%$ more precise than m_{top} @ 7 TeV



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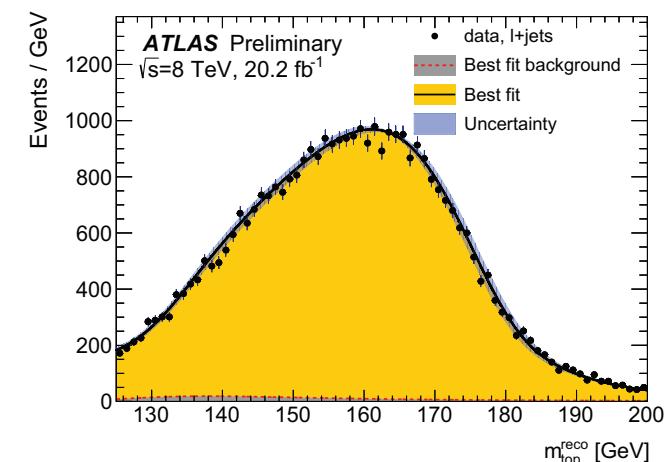


Lepton+jets m_{top} measurement at 8 TeV

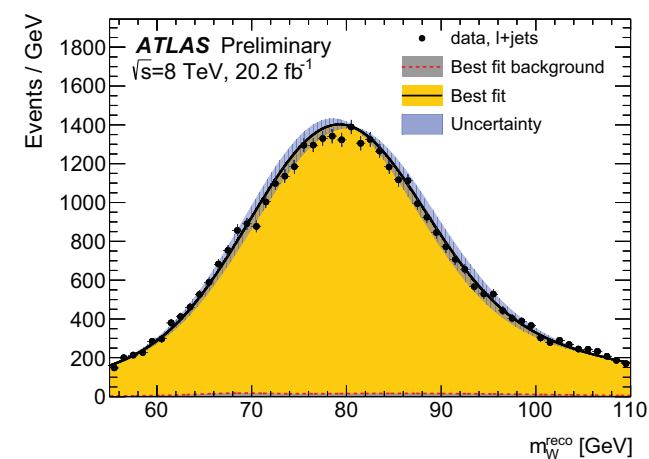
- ▶ Direct: m_{top} measurement from $t\bar{t}$ lepton+jets channel
- ▶ Basic selection:
 - ≥ 1 lepton, ≥ 4 central ($|\eta| < 2.5$) jets two of them b-jets
 - In $t\bar{t} \rightarrow \mu + \text{jets}$ ($t\bar{t} \rightarrow e + \text{jets}$) events, use $E_T^{\text{Miss}} > 20(30)$ GeV and $E_T^{\text{Miss}} + m_W^W > 60(30)$ GeV
- ▶ Event kinematic reconstruction based on a likelihood fit performed with the KLFitter package
- ▶ Measurement of m_{top} based on an optimization of the selection based on a boosted decision tree (BDT)
- ▶ Use 3-dimensional template fit to determine m_{top} with the jet energy scale factor (JSF) and the relative b-to-light-jet energy scale factor (bJSF)
- ▶ $m_{\text{top}} = 172.08 \pm 0.39 \text{ (stat)} \pm 82 \text{ (syst)} \text{ GeV}$
- ▶ Biggest systematic uncertainties: JES, and bJES
- ▶ Combining this m_{top} with the dilepton m_{top} at 7 and 8 TeV, and lepton+jets at 7 TeV:

$$m_{\text{top}} = 172.51 \pm 0.27 \text{ (stat)} \pm 0.42 \text{ (syst)} \text{ GeV}$$

$t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}' b\ell\nu\bar{b}$
ATLAS-CONF-2017-071



(a) Reconstructed top quark mass



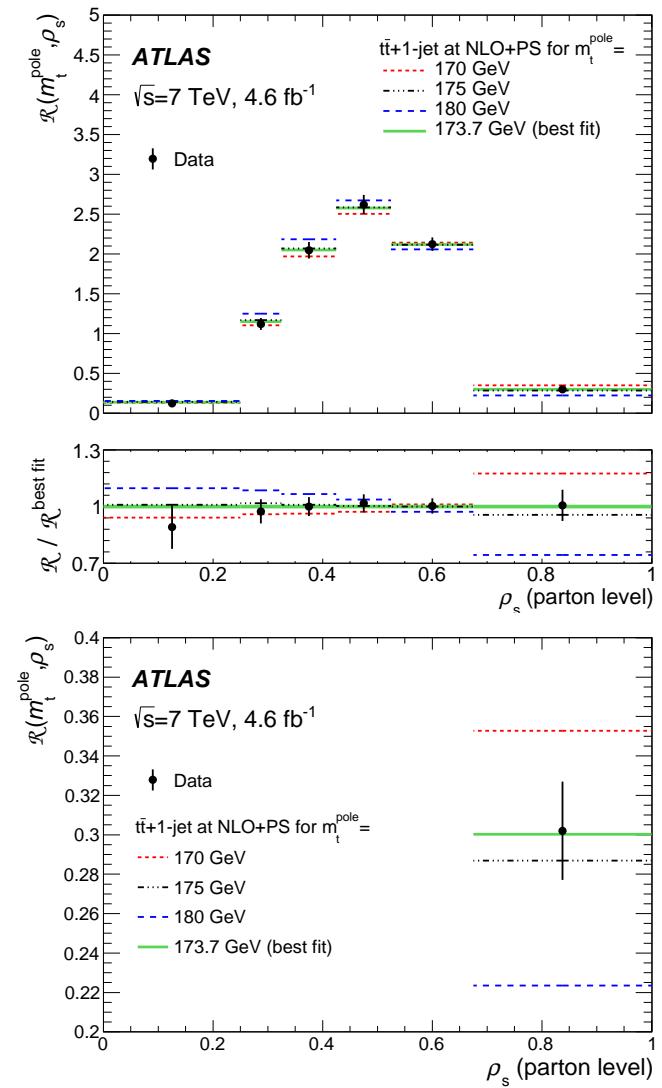
(b) Reconstructed W boson mass



m_{top}^{pole} measurement in $t\bar{t} + 1\text{jet}$ events at 7 TeV

- ▶ Indirect: m_{top}^{pole} measurement from comparison of NLO prediction with the normalized differential cross-section in $t\bar{t} + 1\text{jet}$ events at 7 TeV
 - ▶ Select semileptonic $t\bar{t}$ events with two b -jets
 - Mass jets pair (m_{jj}) consistent with W boson:
 $0.9 < \alpha = m_W/m_{jj} < 1.25$
 $(m_W^{\text{ref}} = 80.4 \text{ GeV})$, and correct with α
 - Further requirement $m_{top}^{\text{lep}}/m_t^{\text{hadro}} > 0.9$
 - ▶ m_t^{pole} obtained from fit to the normalized diff. cross-section $\mathcal{R}(m_t^{pole}, \rho_s)$ for $t\bar{t} + 1\text{jet}$ production as a function of the inverse of the invariant mass of the $t\bar{t} + 1\text{jet}$ system, ρ_s .
 - ▶ Most sensitive bin $0.675 < \rho_s < 1$
 - ▶ Prediction of $t\bar{t} + 1\text{jet}$ at NLO+PS using $m_{top}^{pole} = 170, 175, 180 \text{ GeV}$ is compared with m_{top}^{pole} extracted from best fit
- $m_{top}^{pole} = 173.7 \pm 1.5(\text{stat}) \pm 1.4(\text{syst})^{+1.0}_{-0.5}(\text{th}) \text{ GeV}$

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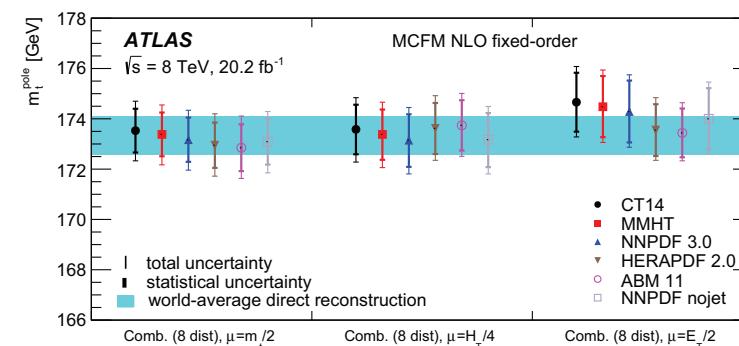
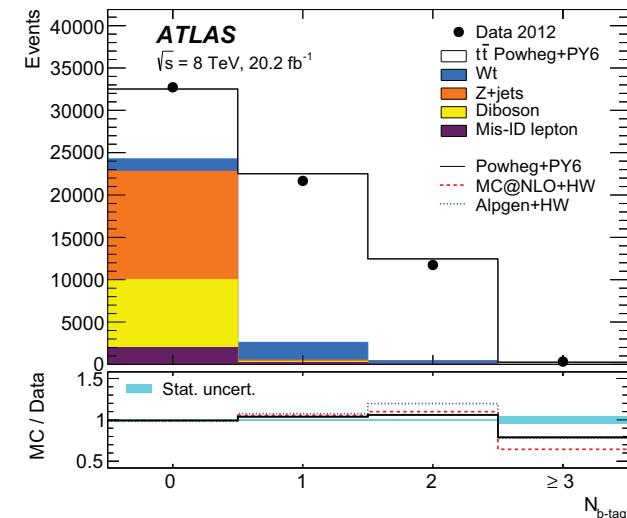
m_{top}^{pole} measurement in dilepton $t\bar{t}$ events at 8 TeV

- Indirect: m_{top}^{pole} from measurement of cross-sections with oppositely charged dilepton ($e \mu$) final states at 8 TeV
- Select dileptonic $t\bar{t}$ events with two b -jets
- Eight differential cross-section distributions are measured for $t\bar{t} \rightarrow e\mu\nu\nu bb$:
 - p_T^ℓ , $|\eta^\ell|$, $p_T^{e\mu}$, $m^{e\mu}$, $p_T^e + p_T^\mu$, $E^e + E^\mu$, p_T , $|y^{e\mu}|$, and $\Delta\phi^{e\mu}$
- Various techniques for extracting m_{top}^{pole} explored
- Results are compared to the predictions of various NLO and LO $t\bar{t}$ generators, and to fixed-order perturbative QCD predictions from the MCFM program
- Most precise m_{top}^{pole} extracted from simultaneous fit of fixed-order predictions to all eight measured differential distributions simultaneously

$$m_{top}^{pole} = 173.2 \pm 0.9(\text{stat}) \pm 0.8(\text{syst}) \pm 1.2(\text{th}) \text{ GeV}$$

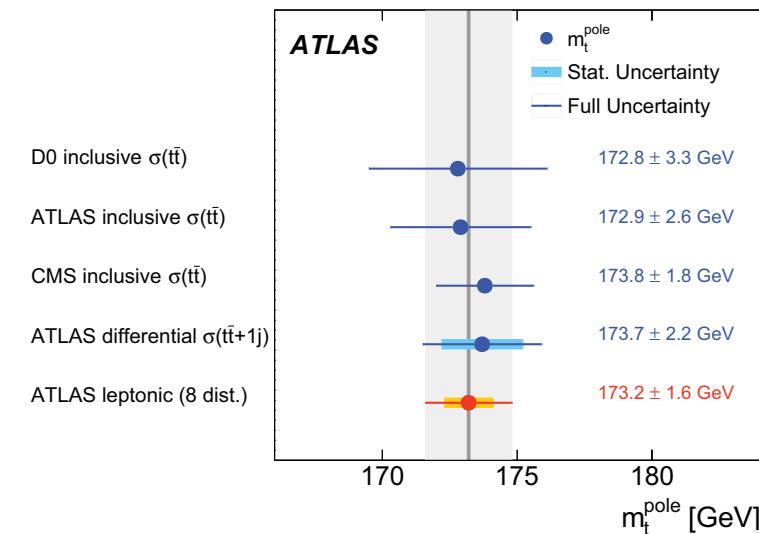
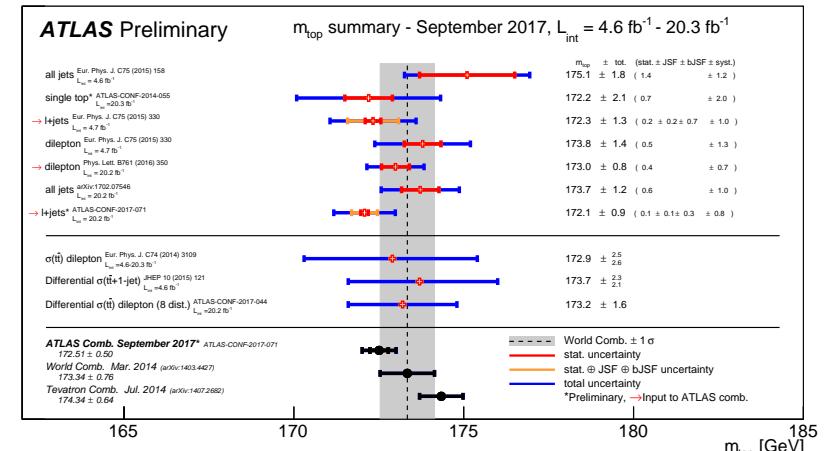
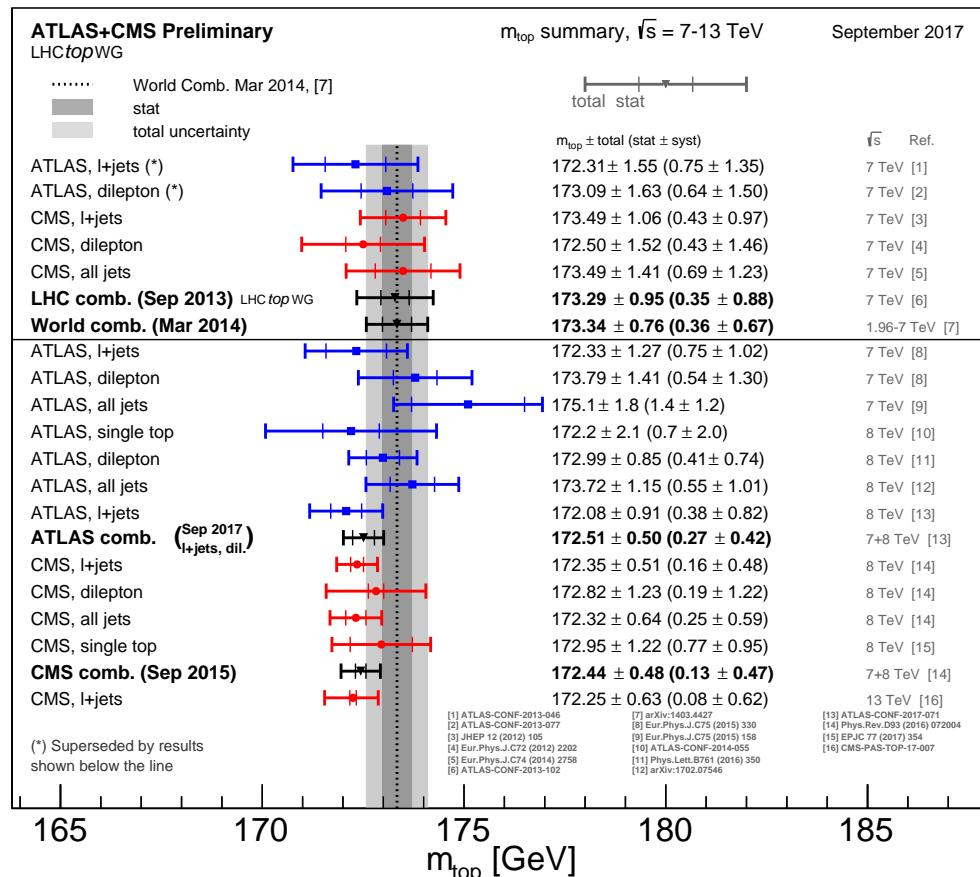
Dominant theoretical uncertainty from QCD scales

EPJ C77 (2017) 804



Direct and indirect summary m_{top} measurements

- Left figure shows summary of ATLAS and CMS direct m_{top} measurements, compared with the LHC and Tevatron+LHC m_{top} combinations. Top right plot shows summary of ATLAS latest direct m_{top} measurements. Bottom right plot shows latest ATLAS indirect $m_{\text{top}}^{\text{pole}}$ determinations.



Conclusions

- ▶ Precise measurements of m_{top} are fundamental to provide inputs to test the self-consistency of the SM and search physics BSM
- ▶ Presented latest ATLAS results of m_{top} and $m_{\text{top}}^{\text{pole}}$ performed using Run1 data at LHC
- ▶ Most precise $m_{\text{top}}^{\text{pole}}$ @ 8 TeV measured in dilepton
$$m_{\text{top}}^{\text{pole}} = 173.2 \pm 0.9(\text{stat}) \pm 0.8(\text{syst}) \pm 1.2(\text{th}) \text{ GeV}$$
- ▶ Most precise single m_{top} measurement in the dilepton channel
$$m_{\text{top}} = 172.99 \pm 0.41 \text{ (stat)} \pm 0.74 \text{ (syst)} \text{ GeV}$$
- ▶ Most recent m_{top} measurement in all-jets and in lepton+jets channel @ 8 TeV:
$$m_{\text{top}} = 173.72 \pm 0.55 \text{ (stat)} \pm 1.01 \text{ (syst)} \text{ GeV}$$

$$m_{\text{top}} = 172.08 \pm 0.39 \text{ (stat)} \pm 0.82 \text{ (syst)} \text{ GeV}$$
- ▶ Combining the lepton + jets and dilepton m_{top} result @ 8 TeV and @ 7 TeV
$$m_{\text{top}} = 172.51 \pm 0.27 \text{ (stat)} \pm 0.42 \text{ (syst)} \text{ GeV}$$
- ▶ With this precision the relation between m_{top} definition of the experimental analysis and the $m_{\text{top}}^{\text{pole}}$ is becoming relevant
- ▶ m_{top} measurements dominated by systematic uncertainties
- ▶ We will continue looking at more interesting measurements done using Run2 data at LHC with the challenge to bring the systematics uncertainties down

