Standard Model physics with ATLAS

A selection of results with major MPP contributions

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Ben Pearson
on behalf of the MPP ATLAS Group

ATLAS EXPERIMENT

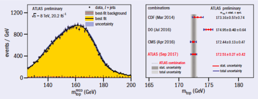
CERNCOURIER
Volume 57 Number 9 November 2017

ATLAS experiment makes precision measurement of top-quark mass

The top quark is copiously produced at the LHC, allowing for very precise measurements of its properties. The mass of the top quark, m_{top}, plays a special role in the Standard Model (SM) of particle physics. It is a key part of the mechanism of electroweak symmetry breaking and one of the parameters governing the stability of the universe in the SM.

Following years of meticulous work, ATLAS presented a new measurement of m_{top} at the 10th International Workshop on Top Quark Physics held in Braga, Portugal, in late September. The measurement was performed using around 100,000 proton–proton collision events at an energy of 8 TeV, each containing a top-quark pair reconstructed in the single-lepton final state. In this channel, each top quark immediately decays to a W boson and a bottom quark, and one W boson decays to an electron or muon and a neutrino, while the second W boson decays to two light quarks.

A simultaneous measurement of m_{top} together with a global jet-energy scale factor and a relative bottom-to-light jet-energy scale factor was performed. The inclusion of these scale factors strongly reduces systematic uncertainties. The precision of the measurement is further improved by differentiating between correctly reconstructed top-quark events and events where the final-state objects are incorrectly assigned to the two top quarks. While only retaining 40% of the events, the total uncertainty is improved by 19%, leading to a top-quark mass of 172.08±0.91 GeV.



(Left) The reconstructed top-quark mass recorded at 8 TeV together with the best-fit template. (Right) the new ATLAS combined result compared to those from other experiments.

The power of this measurement, which is the second most precise individual top-quark mass measurement made by ATLAS to date, is revealed when combined with previous ATLAS measurements in the single-lepton channel at 7 TeV and the dilepton channel at 8 TeV. This combination relies on a careful evaluation of the correlation between measurements for all sources of systematic uncertainty. In both channels at 8 TeV, the analysis optimisation trades reduced systematic against increased statistical uncertainty, thereby reducing the correlation among the measurements. The combined result thus has a 41% smaller uncertainty than the single most precise measurement. The current combined value is 172.51±0.50 GeV with a relative precision of 0.29%, which is mainly limited by the calibration of the jet-energy scales and is similar to that of the leading single-experiment combined measurements.

The current precision on m_{top} represents a significant achievement that demonstrates the precise understanding of all the relevant aspects of the ATLAS detector. The measurement will allow further and deeper tests of the consistency of the SM.

Further reading

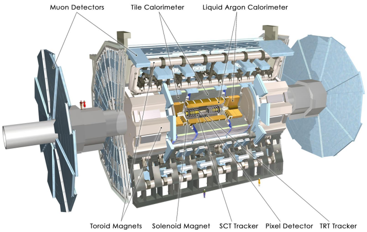
ATLAS Collaboration 2017 ATLAS-CONF-2017-071.

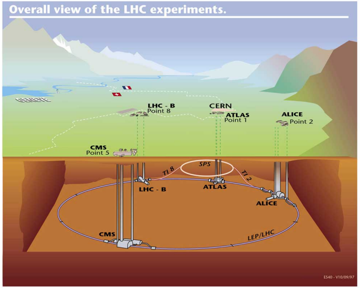
MPP Project Review 2017

18-19 December 2017 || Munich, Germany

Outline

- Dataset used
  - $20.2\ \text{fb}^{-1}$ of pp collision data recorded by ATLAS
  - Collisions provided by the LHC at a centre-of-mass energy of $\sqrt{s} = 8\,\text{TeV}$
- Measurements made
  - WW/WZ (WV or diboson) production in semi-leptonic decays [1]
    - ★ Fiducial cross-section measurement
    - ★ Search for anomalous triple gauge-boson couplings (aTGCs)
  - Top quark mass (m_{top}) measurements
    - ★ In the $t\bar{t} \to$ all-jets channel [2]
    - ★ In the $t\bar{t} \to$ lepton+jets channel [3]
    - ★ New ATLAS combination [3]
- Conclusions

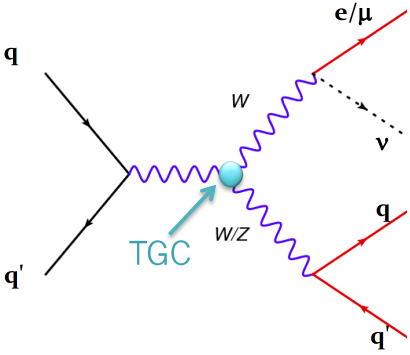


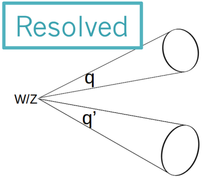


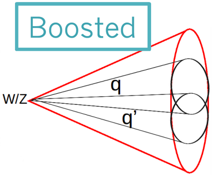
[1] Eur. Phys. J. C 77 (2017) 563 || [2] JHEP 09 (2017) 118 || [3] ATLAS-CONF-2017-071

WV cross-section and search for aTGCs

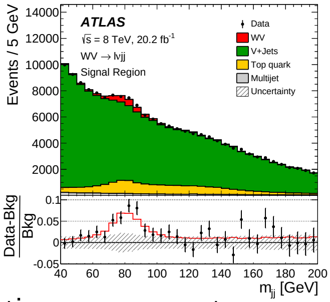
- Motivation
  - Measurements of diboson production are powerful probes of the electroweak part of the Standard Model (SM)
    - Especially the structure of the TGC
  - Cannot separate *WW* from *WZ*, so combine as *WV*
- Goals
  - Measure the semi-leptonic $WV \to \ell\nu qq$ cross-section
  - Search for beyond-the SM (BSM) enhancements of diboson production in the form of aTGCs
- Analysis channels
  - **Resolved** topology
    - Hadronic W/Z reconstructed as two separate jets (jj)
  - **Boosted** topology
    - Hadronic W/Z reconstructed as one large-R jet (J)

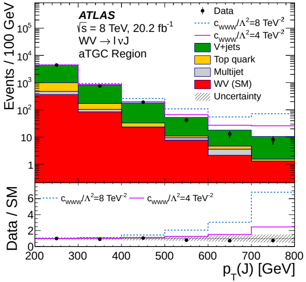






Measurement strategy





Cross-section measurement:

- Signal-to-background ratio (S/B)
  - $\sim 5\%$ ($\sim 10\%$) for resolved (boosted)
  - Dominant background: W+jets

t

- Signal extracted by Maximum-Likelihood (ML) fit to the dijet mass (m_{jj}) or the mass of the large-R jet (m_J)

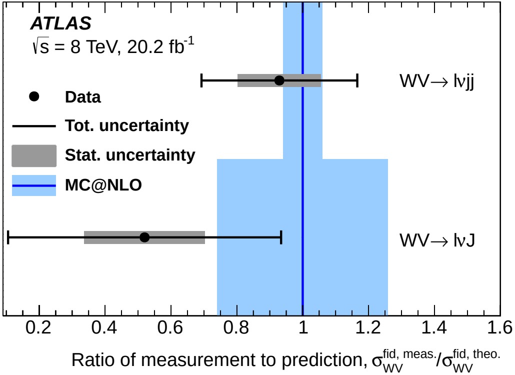
Search for aTGCs:

- aTGCs enhance the event rate of bosons with high transverse momentum (p_{T})
  - Search for deviations from the SM in the $p_{\mathrm{T}}(jj)$ and $p_{\mathrm{T}}(J)$ distributions
- Added event requirement to increase S/B
  - $65\ \mathrm{GeV} < m_{jj}/m_J < 95\ \mathrm{GeV}$

Results

Extracted fiducial cross-section results:

- Resolved channel: $\sigma_{\text{fid}} = 209 \pm 28\ (\text{stat}) \pm 45\ (\text{syst})$ fb $\rightarrow$ 4.5σ significance
- Boosted channel: $\sigma_{\text{fid}} = 30 \pm 11\ (\text{stat}) \pm 22\ (\text{syst})$ fb $\rightarrow$ 1.3σ significance
- Dominant systematic uncertainties from MC modelling



Search results for aTGCs:

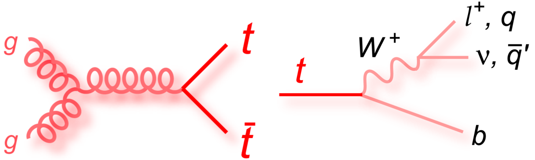
- No significant deviation from the SM prediction is observed
- Constraints computed for aTGC parameters
- Boosted channel significantly more sensitive to the new-physics parameters
- Constraints are comparable to previous most-stringent constraints from other diboson analyses

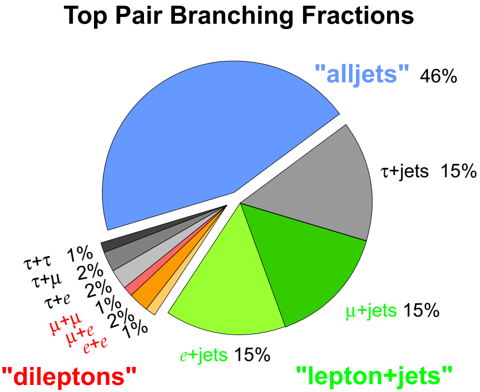
The top quark

- Heaviest elementary particle discovered
  - Decays before it can hadronise
    - $t \to Wb$ nearly 100% of the time
- m_{top} is a fundamental parameter of the SM important for:
  - Precision tests of the SM
  - Tests of new physics scenarios

The LHC is a top quark factory

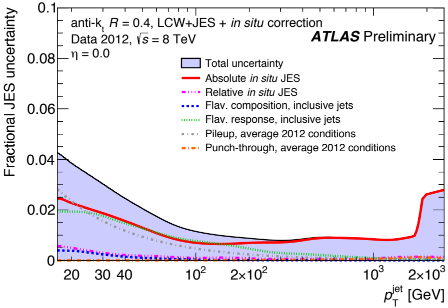
- Primarily produced is pairs ($t\bar{t}$)
- $t\bar{t}$ decay channels defined by W decays
  - **all-jets**: highest rate, but largest background
  - **lepton+jets**: medium rate, but better purity
  - **dilepton**: lowest rate and incomplete kinematics, but best purity





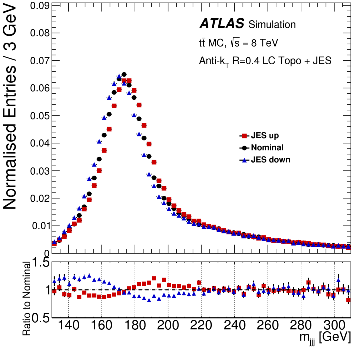
m_{top} measurements: Strategies

- Direct measurements of m_{top} in ATLAS use the template method
  - Reconstructed variable distributions sensitive to m_{top} are fit to analytical functions parameterised as functions of the input top quark mass
- However, reconstruction of the $t\bar{t}$ decay requires the use of jets
  - Large sensitivity to uncertainties in the jet energy scale (JES) and b-to-light jet energy scale (bJES)
    - ★ If directly translated: $0.01 \times m_{\text{top}} \approx 1.7$ GeV!!
- Two primary strategies to reduce the uncertainty in m_{top} induced by variations in the JES
  - I. Find an m_{top}-sensitive variable with some built-in protection (e.g. all-jets measurement)
  - II. Make an in-situ calibration of global jet energy scale factors (e.g. lepton+jets measurement)

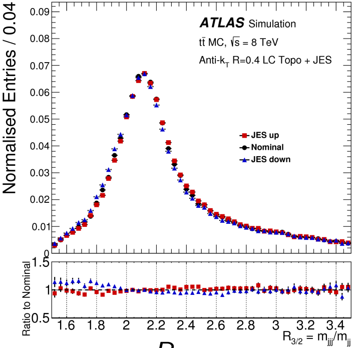


m_{top} in the $t\bar{t} \rightarrow$ all-jets channel: Strategy I

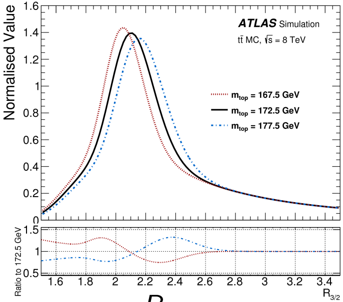
- Use a 1-Dimensional (1-D) template method
- Use the $R_{3/2}$ distribution as the estimator for m_{top}: $R_{3/2} = \frac{m_{qqb}}{m_{qq}} \propto$ " $\frac{\text{JES}*\text{bJES}}{\text{JES}}$ "
  - Protected from variations in the JES (see comparison to m_{jjj} below left $\rightarrow$ middle)
  - Retains good sensitivity to m_{top} (see below right)



m_{jjj}



$R_{3/2}$



$R_{3/2}$

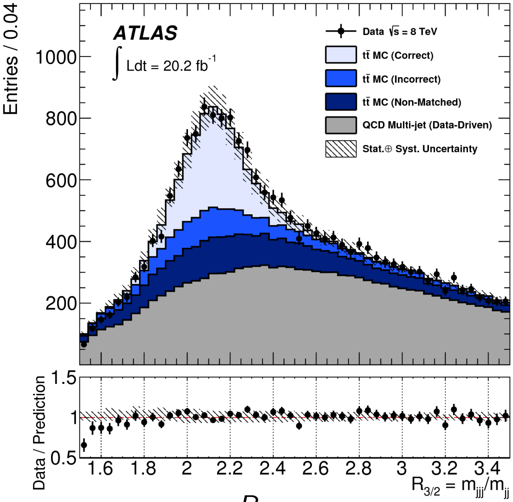
Background

Event topology

- Require at least **6** high-p_T central jets and a **veto on leptons**
  - At least **two** jets must be ***b*-tagged**

Background fraction is large: $> 60\%$

- Made up of QCD multi-jet events
- Three control regions are used to determine the shape of the background from the data
  - The final background normalisation in the signal region is a free parameter in the m_{top}-extraction fit to the data



$R_{3/2}$

Results

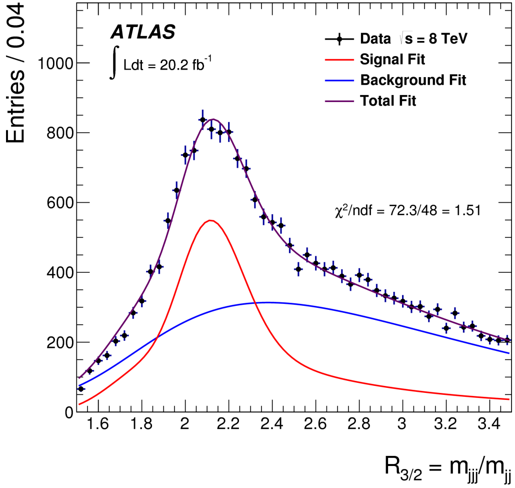
- A binned minimum χ^2 fit to the observed data results in

$$\boldsymbol{m_{top} = 173.72 \pm 0.55(\text{stat}) \pm 1.01(\text{syst})\ \text{GeV}}$$

with a total uncertainty of

1.15 GeV

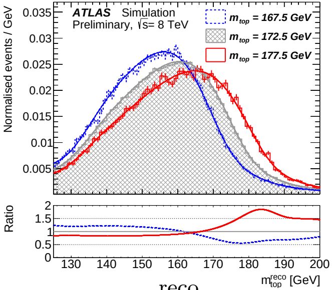
- Dominant systematic uncertainties (Δm_{top})
  - hadronisation modelling (0.64 GeV)
  - JES (0.60 GeV)
- 0.66% precision in m_{top}
- 36% improvement over the 7 TeV all-jets measurement



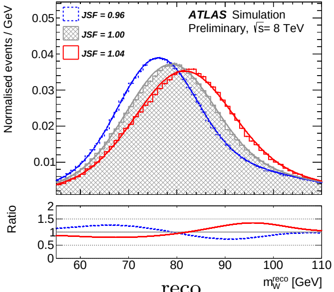
m_{top} in the $t\bar{t} \to$ lepton+jets channel: Strategy II

- Make a simultaneous measurement of m_{top} with a jet energy scale factor (JSF) and a relative b-to-light-jet energy scale factor (bJSF)
- Use a multi-variate template method (developed in the 7 TeV lepton+jets analysis)
  - Templates constructed from simulated distributions of $m_{\text{top}}^{\text{reco}}$, m_W^{reco}, and R_{bq}^{reco}

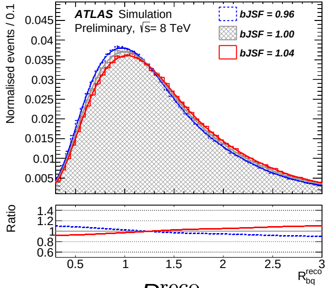
$$R_{bq}^{\text{reco}} = \frac{p_{\text{T}}^{b_{\text{had}}} + p_{\text{T}}^{b_{\text{lep}}}}{p_{\text{T}}^{q_1} + p_{\text{T}}^{q_2}} \propto \text{"}\frac{\text{JSF} * \text{bJSF}}{\text{JSF}}\text{"},$$ where q_1 and q_2 are light jets from the W boson



$m_{\text{top}}^{\text{reco}}$



m_W^{reco}



R_{bq}^{reco}

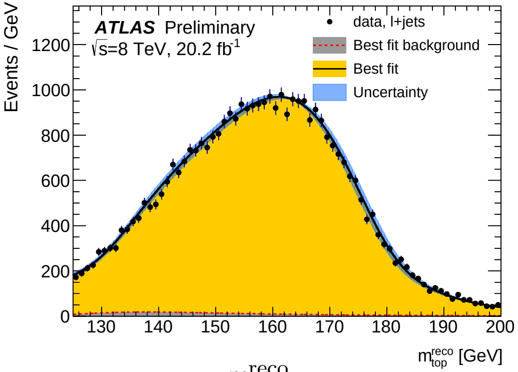
Results

- Simultaneous unbinned maximum likelihood fit to the distributions in data results in

$$m_{top} = 172.08 \pm 0.39(\text{stat}) \pm 0.82(\text{syst})\ \text{GeV}$$

with a total uncertainty of **0.91 GeV** (0.53%)

- Dominant sources of uncertainty
  - JES (0.54 GeV) and *b*-tagging (0.38 GeV)
- 29% improvement over the 7 TeV m_{top}^{l+jets}
- Traded large sample size for smaller total uncertainty using a sample reduction via a multivariate analysis (BDT)
  - Reduces the total uncertainty by 19%!!
  - Resolution improves considerably
    - ★ Removes 60% of events with very little increase in statistical uncertainty

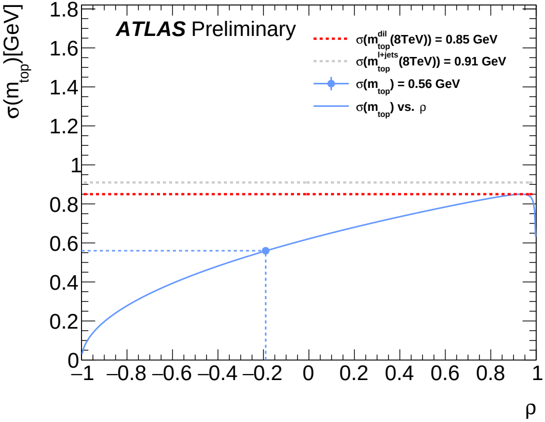


m_{top}^{reco}

- Yellow filled area is best fit to data
- Blue band is $\pm 1\sigma$ uncertainty on the fit

m_{top} combination: example with the two most precise ATLAS results

- Example combination of the two most precise measurements
- The **red** and **gray** lines indicate the precision of the input measurements
- The **blue curve** shows the uncertainty in the example combination as a function of the total correlation of the input measurements
  - **Correlation is of utmost importance**
- Careful **evaluation** of the estimator correlation for each source of uncertainty reveals small correlations
  - Much smaller than what is usually assigned



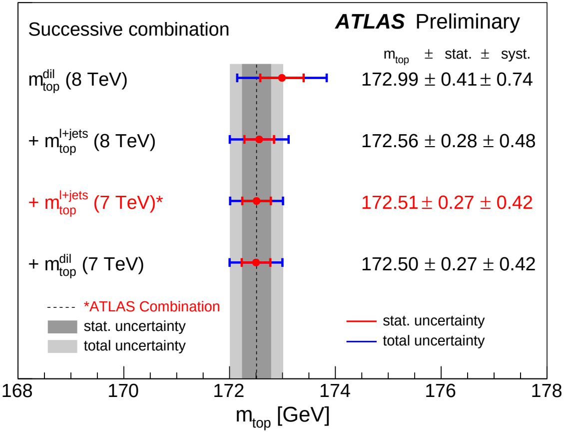
New preliminary ATLAS combination of m_{top}

- Evolution of the combination when adding one measurement at a time
  - all-jets measurements not yet included
- No significant improvement is observed below the line in red
- New preliminary ATLAS combination:

  $$m_{\text{top}}^{\text{comb}} = 172.51 \pm 0.50 \text{ GeV}$$

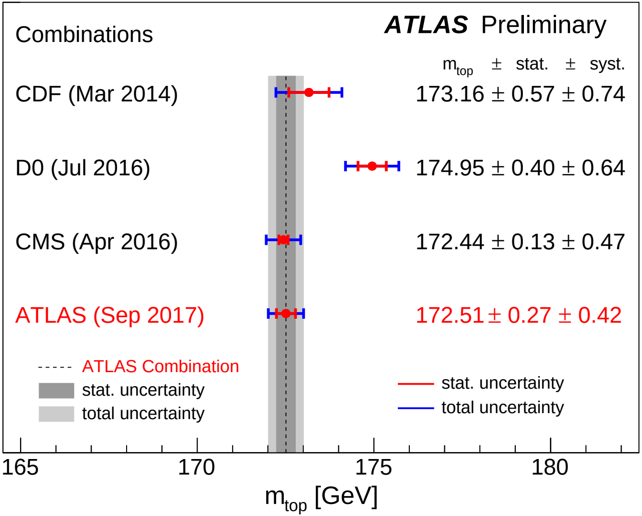
- Compare to the previous ATLAS combination:

  $$m_{\text{top}}^{\text{comb}} = 172.84 \pm 0.70 \text{ GeV}$$



- a 29% improvement w.r.t. the previous ATLAS combination
- a 41% improvement w.r.t. the most precise input measurement

- LHC combinations have smaller systematic uncertainties than Tevatron ones
- ATLAS and CMS combinations nearly coincide and have comparable precision
  - CMS has more precise individual measurements
  - ATLAS has smaller correlations



Conclusions and remarks

- WV production measurements
  - Resolved channel observed significance of 4.5σ
  - Boosted channel observed significance of 1.3σ
  - No deviation from the SM $\rightarrow$ constraints on aTGCs
- ATLAS has measured m_{top} in all three $t\bar{t}$ decay channels at two collision energies
  - Individual results since last MPP Project Review (all at $\sqrt{s} = 8\,\mathrm{TeV}$)
    - ★ $m_{\mathrm{top}}^{\mathrm{dil}} = 172.99 \pm 0.84$ GeV
    - ★ $m_{\mathrm{top}}^{\mathrm{all-jets}} = 173.72 \pm 1.15$ GeV
    - ★ $m_{\mathrm{top}}^{\mathrm{l+jets}} = 172.08 \pm 0.91$ GeV
  - New ATLAS combination
    - ★ $m_{\mathrm{top}}^{\mathrm{comb}} = 172.51 \pm 0.50$ GeV
- Outlook
  - Include all-jets measurements in combination
  - Move to 13 TeV m_{top} analyses

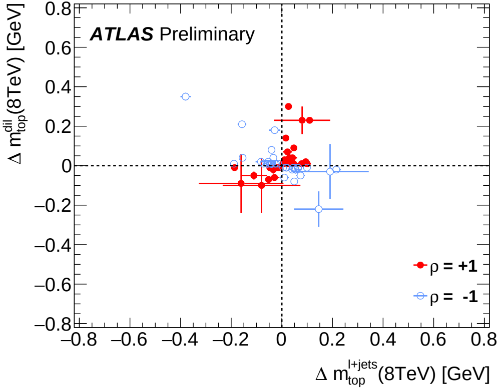
Additional Material

Summary of direct ATLAS m_{top} measurements

	$m_{top}^{all-jets}$ [GeV]		m_{top}^{l+jets} [GeV]		m_{top}^{dil} [GeV]	
	7 TeV	**8 TeV**	**7 TeV**	**8 TeV**	**7 TeV**	**8 TeV**
m_{top}	175.06	173.72	172.33	172.08	173.79	172.99
Statistical unc.	1.35	0.55	0.75	0.39	0.54	0.41
Dominant syst. unc.	JES: 0.60 bJES: 0.62	JES: 0.60 Had: 0.64	JES: 0.58 *b*-tag: 0.50	JES: 0.54 *b*-tag: 0.38	JES: 0.76 bJES: 0.68	JES: 0.54 bJES: 0.30
Total systematic unc.	1.21 ± 0.16	1.01 ± 0.12	1.04 ± 0.08	0.82 ± 0.06	1.31 ± 0.07	0.74 ± 0.05
Total uncertainty	**1.81 ± 0.16**	**1.15 ± 0.12**	**1.28 ± 0.08**	**0.91 ± 0.06**	**1.42 ± 0.07**	**0.84 ± 0.05**
7 → 8 TeV improvement	36%		29%		40%	

m_{top} combination: example correlations of pairs of estimators

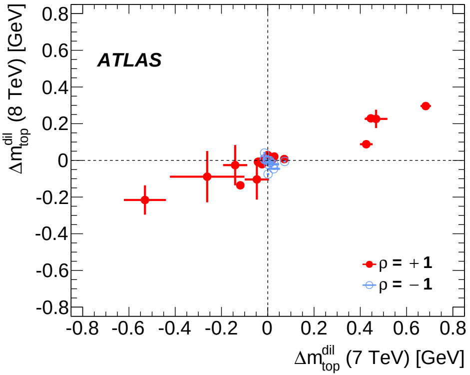
- Combination is performed using the Best Linear Unbiased Estimate (BLUE) method
- Correlations of each pair of measurements are **evaluated** for each uncertainty component
  - Example figure below for the two most precise measurements



- Pairwise Δm_{top} when simultaneously varying the pair of measurements for each systematic uncertainty
- Sizes of crosses indicate statistical precision of the systematic uncertainty components
- Correlated cases $\rightarrow$ red full points
- Anti-correlated cases $\rightarrow$ blue open points
- This pair of measurements has many significant anti-correlated components

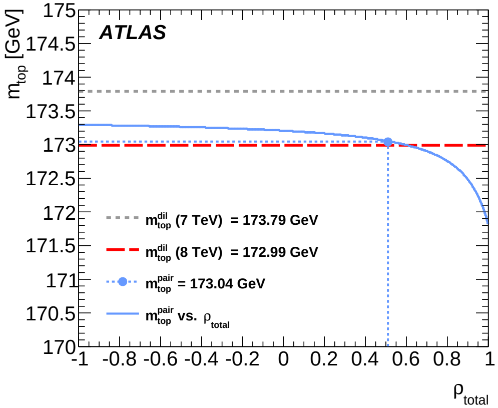
m_{top} combination correlations: 7 and 8 TeV dilepton

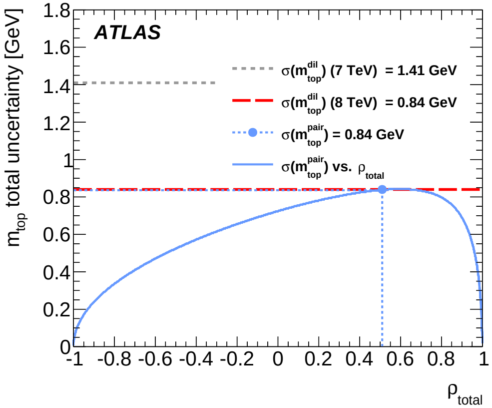
- Combination is performed using the Best Linear Unbiased Estimate (BLUE) method
- Correlations of each pair of measurements are **evaluated** for each uncertainty component



- Pairwise Δm_{top} when simultaneously varying the pair of measurements for each systematic uncertainty
- Sizes of crosses indicate statistical precision of the systematic uncertainty components
- Correlated cases → blue open points
- Anti-correlated cases → red full points
- This pair of measurements is strongly correlated

m_{top} combination results: 7 and 8 TeV dilepton

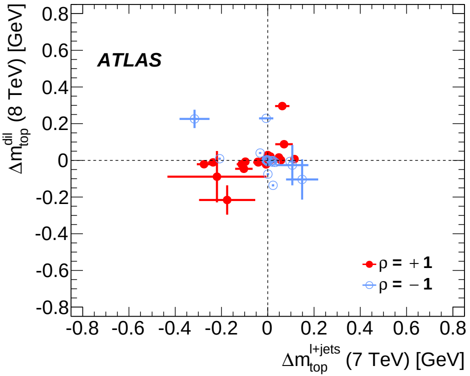




- Combined value (left) and uncertainty (right) in the combination of the 7 and 8 TeV dilepton measurements as a function of their total correlation (blue line)
- The red and gray lines indicate the pair of input values (left) and uncertainties (right)
- The uncertainty in the combined m_{top} strongly depends on the total correlation

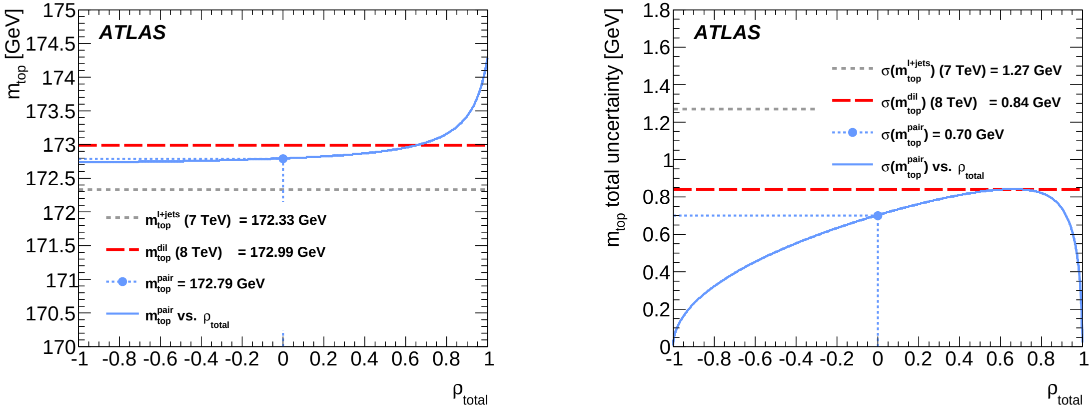
m_{top} combination correlations: 7 TeV lepton+jets and 8 TeV dilepton

- Combination is performed using the Best Linear Unbiased Estimate (BLUE) method
- Correlations of each pair of measurements are **evaluated** for each uncertainty component



- Pairwise Δm_{top} when simultaneously varying the pair of measurements for each systematic uncertainty
- Sizes of crosses indicate statistical precision of the systematic uncertainty components
- Correlated cases $\rightarrow$ blue open points
- Anti-correlated cases $\rightarrow$ red full points
- This pair of measurements has roughly equal correlated and anti-correlated components

m_{top} combination results: 7 TeV lepton+jets and 8 TeV dilepton



- Combined value (left) and uncertainty (right) in the combination of the 7 TeV lepton+jets and 8 TeV dilepton measurements as a function of their total correlation (blue line)
- The red and gray lines indicate the pair of input values (left) and uncertainties (right)
- The uncertainty in the combined m_{top} strongly depends on the total correlation

m_{top} in the $t\bar{t} \rightarrow$ lepton+jets channel: Optimisation

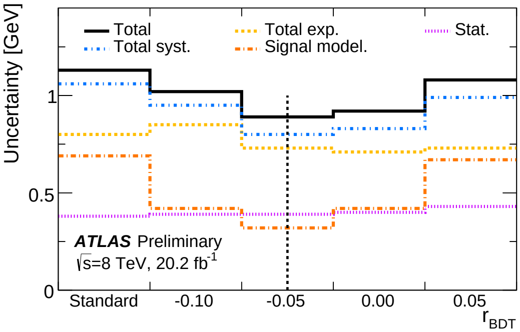
Event topology

- Require **one** high-p_T electron or muon and **at least four** high-p_T central jets
  - Exactly **two** jets must be ***b*-tagged**

Multi-Variate Analysis (MVA) technique

- Train a Boosted Decision Tree (BDT) algorithm on $t\bar{t}$ signal to distinguish wrongly/unmatched events from correctly matched events
  - Wrongly/unmatched events expected to have larger systematic uncertainties
- Chose a cut on the BDT output that minimises the total uncertainty in m_{top}

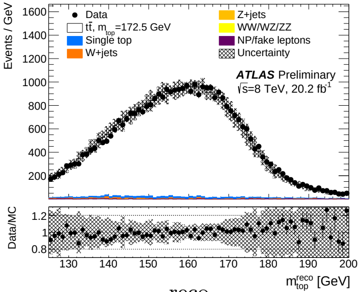
Background fraction is only $\sim 1\%$



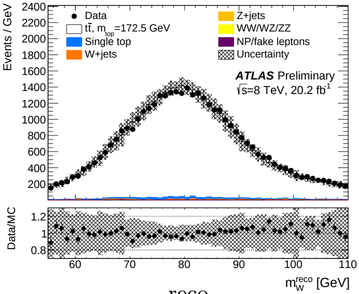
- 19% improvement over no BDT (Standard)
- Reduces theory modelling uncertainties
- Also improves resolution in m_{top} as seen by flatness of the stat. unc. with the loss of $> 60\%$ of events

m_{top} in the $t\bar{t} \rightarrow$ lepton+jets channel: data/MC agreement

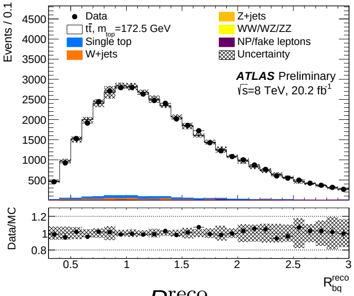
- After applying the r_{BDT} cut, the background fraction is only 1%
- Single-top-quark production is included in signal
  - resulting in a background independent of m_{top}
- Distributions of fit variables agree well with data within uncertainties
  - MC simulation is normalised to the data and only shape uncertainties remain in the band



$m_{\text{top}}^{\text{reco}}$



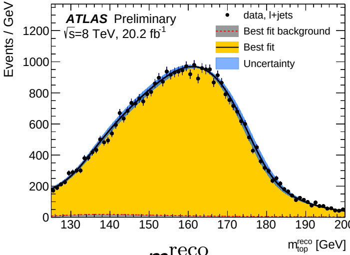
m_W^{reco}



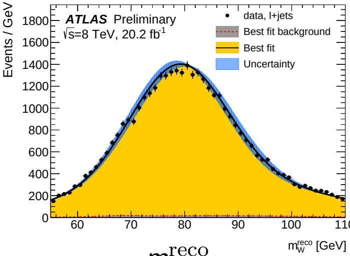
R_{bq}^{reco}

- The simultaneous unbinned maximum likelihood fit to the three distributions in data results in:

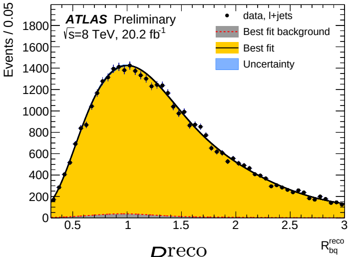
$m_{\mathrm{top}} = 172.08 \pm 0.39(\mathrm{stat})$ GeV $\mathrm{JSF} = 1.005 \pm 0.001(\mathrm{stat})$ $\mathrm{bJSF} = 1.008 \pm 0.005(\mathrm{stat})$



$m_{\mathrm{top}}^{\mathrm{reco}}$



m_{W}^{reco}



R_{bq}^{reco}

- Including systematic uncertainties, the result is:

$$\mathbf{m_{top} = 172.08 \pm 0.39(stat) \pm 0.82(syst)\ GeV = 172.08 \pm 0.91\ GeV}$$

m_{top} in the $t\bar{t} \to$ lepton+jets channel: uncertainties in m_{top}

- Dominant sources of uncertainty
  - JES (0.54 GeV) and b-tagging (0.38 GeV)
- Total uncertainty reduced with BDT sel.
  - 19% improvement over no BDT at 8 TeV
  - Reduces theory modelling uncertainties
  - Also improves resolution in m_{top} as seen by the scaling of the stat. unc.
    - With no improvement in resolution: $\sigma^{\text{stat}}_{\text{BDT}} = \sigma^{\text{stat}}_{\text{std}} \sqrt{N_{\text{std}}/N_{\text{BDT}}} = 0.60$ as compared to 0.39
  - Altogether, a **29%** improvement over the 7 TeV lepton+jets measurement

	m_{top} [GeV]		
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	
Event selection	Standard	Standard	BDT
Result	172.33	171.90	172.08
Statistics	0.75	0.38	0.39
– *Stat. comp.* (m_{top})	0.23	0.12	0.11
– *Stat. comp.* (JSF)	0.25	0.11	0.11
– *Stat. comp.* (bJSF)	0.67	0.34	0.35
Method	0.11 ± 0.10	0.04 ± 0.11	0.13 ± 0.11
Signal Monte Carlo generator	0.22 ± 0.21	0.50 ± 0.17	0.16 ± 0.17
Hadronisation	0.18 ± 0.12	0.05 ± 0.10	0.15 ± 0.10
Initial- and final-state QCD radiation	0.32 ± 0.06	0.28 ± 0.11	0.08 ± 0.11
Underlying event	0.15 ± 0.07	0.08 ± 0.15	0.08 ± 0.15
Colour reconnection	0.11 ± 0.07	0.37 ± 0.15	0.19 ± 0.15
Parton distribution function	0.25 ± 0.00	0.08 ± 0.00	0.09 ± 0.01
Background normalisation	0.10 ± 0.00	0.04 ± 0.00	0.08 ± 0.00
W+jets shape	0.29 ± 0.00	0.05 ± 0.00	0.11 ± 0.00
Fake leptons shape	0.05 ± 0.00	0	0
Jet energy scale	0.58 ± 0.11	0.63 ± 0.02	0.54 ± 0.02
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.05 ± 0.01	0.03 ± 0.01
Jet energy resolution	0.22 ± 0.11	0.23 ± 0.03	0.20 ± 0.04
Jet reconstruction efficiency	0.12 ± 0.00	0.04 ± 0.01	0.02 ± 0.01
Jet vertex fraction	0.01 ± 0.00	0.13 ± 0.01	0.09 ± 0.01
b-tagging	0.50 ± 0.00	0.37 ± 0.00	0.38 ± 0.00
Leptons	0.04 ± 0.00	0.16 ± 0.01	0.16 ± 0.01
$E_{\text{T}}^{\text{miss}}$	0.15 ± 0.04	0.08 ± 0.01	0.05 ± 0.01
Pile-up	0.02 ± 0.01	0.14 ± 0.01	0.15 ± 0.01
Total systematic uncertainty	1.03 ± 0.08	1.07 ± 0.10	0.82 ± 0.06
Total	1.27 ± 0.08	1.13 ± 0.10	0.91 ± 0.06

m_{top} in the $t\bar{t} \rightarrow$ all-jets channel: Extras

- Sources of uncertainty in m_{top}
  - See table $\rightarrow$
- Functional form for fit
  - Signal: sum of a Novosibirsk function and a Landau function
  - Background: sum of a Gaussian function and a Landau function

Source of uncertainty	Δm_{top} [GeV]
Monte Carlo generator	0.18 ± 0.21
Hadronisation modelling	0.64 ± 0.15
Parton distribution functions	0.04 ± 0.00
Initial/final-state radiation	0.10 ± 0.28
Underlying event	0.13 ± 0.16
Colour reconnection	0.12 ± 0.16
Bias in template method	0.06
Signal and bkgd parameterisation	0.09
Non all-hadronic $t\bar{t}$ contribution	0.06
ABCD method *vs.* ABCDEF method	0.16
Trigger efficiency	0.08 ± 0.01
Lepton/$E_{\mathrm{T}}^{\mathrm{miss}}$ calibration	0.02 ± 0.01
Overall flavour-tagging	0.10 ± 0.00
Jet energy scale (JES)	0.60 ± 0.05
b-jet energy scale (bJES)	0.34 ± 0.02
Jet energy resolution	0.10 ± 0.04
Jet vertex fraction	0.03 ± 0.01
Total systematic uncertainty	1.01
Total statistical uncertainty	0.55
Total uncertainty	1.15

WV analysis: Confidence intervals for aTGC in EFT

- The constraints computed for aTGC parameters can be re-interpreted as constraints on parameters in an effective field theory (EFT)
  - Assuming the "LEP constraint" only three free parameters remain
  - The resulting confidence intervals are shown in the figures below
  - Each parameter is constrained while the other two are fixed to 0 (their SM expectation)