Max-Planck-Institut für Physik
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Top Quark Mass Measurements with the ATLAS Detector

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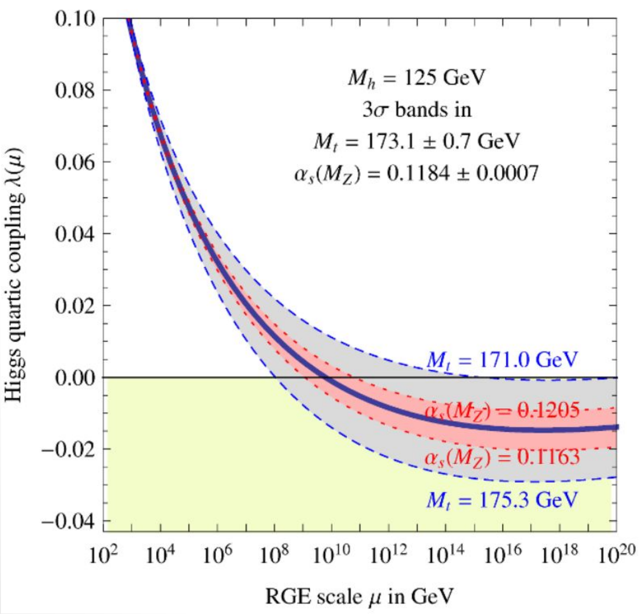
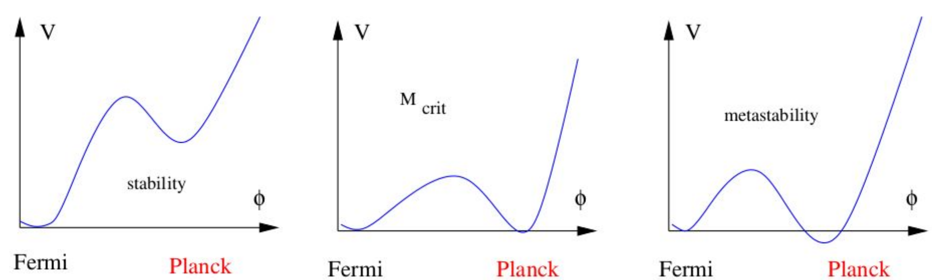
Top Quark Physics - Introduction

- The top quark is the heaviest known fundamental building block
- Its mass is a free fundamental parameter of the Standard Model (SM)
- World combination 2014 of Tevatron and LHC data
  - m_{top} = 173.34 ± 0.27 (stat) ± 0.71 (syst) GeV, total: 0.6% (arXiv:1403.4427)
- m_{top} is an important ingredient for the consistency of the SM
  - especially in conjunction with the mass of the Higgs Boson
  - a low m_{Higgs} around 125-130 GeV leads to a stable vacuum if the Higgs quartic coupling ƛ is small at the Planck scale (~10^{19} GeV)
  - it depends on m_{Higgs} and m_{top} at which scale ƛ becomes small (or negative)



JHEP 1208 (2012) 098

picture from arXiv:1311.4979



$$V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$$

Top Quark Mass - Direct Measurements

- In ATLAS, direct measurements of the top quark are all performed with the template method
- Choose a reconstructible quantity which depends on the top quark mass
  - this is the estimator for the top quark mass measurements
- Construct templates (histograms) with the estimator at various Monte Carlo (MC) input top quark mass values
- Fit the templates with suitable functions (gauss, landau, novosibirsk, …)
- Linearize the parameters of these functions (gauss mean, width, …) as a function of the Monte Carlo input top mass
- Perform a combined log likelihood fit to the distribution of the estimator in data and extract the top quark mass

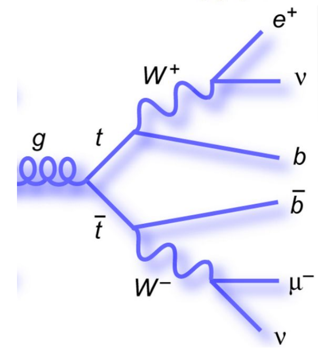
- The measured mass is the one defined in the MC generator
- Its exact theoretical definition is not yet defined
  - expected to be close to the pole mass (within about 1 GeV)

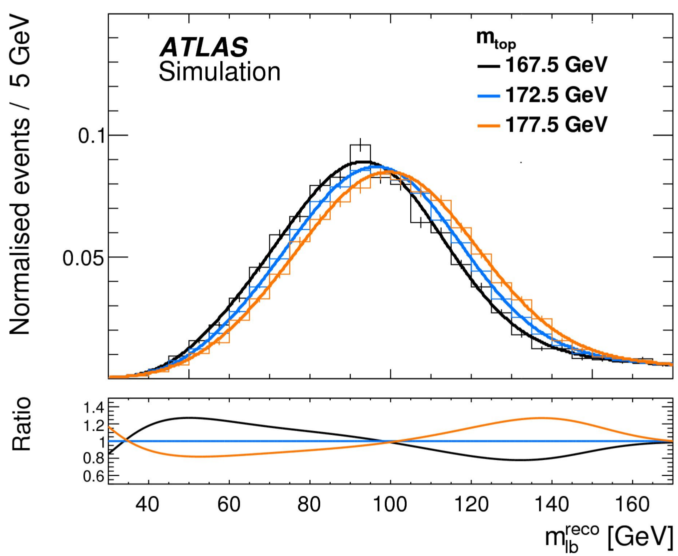
Dilepton channel at 8 TeV

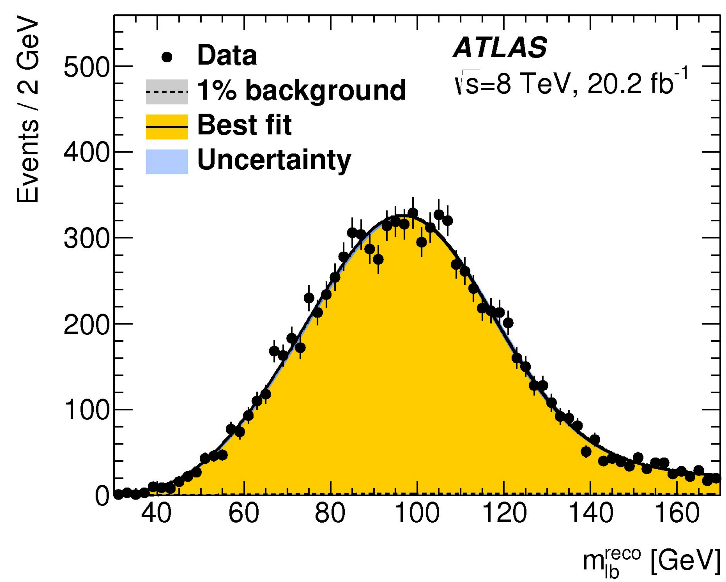
arXiv:1606.02179

NEW!

- Low branching ratio ~4%, very clean: background <1%
- Select events where both W's decay leptonical (eν or $\mu\nu$)
  - Underconstrained final state due to 2 neutrinos
- Partially reconstruct final state and use invariant mass of lepton-b-jet pairs (m_{lb}) as top quark mass dependent estimator







$$m_{top} = 172.99 \pm 0.41\,(\text{stat}) \pm 0.74\,(\text{syst})\ \text{GeV}$$

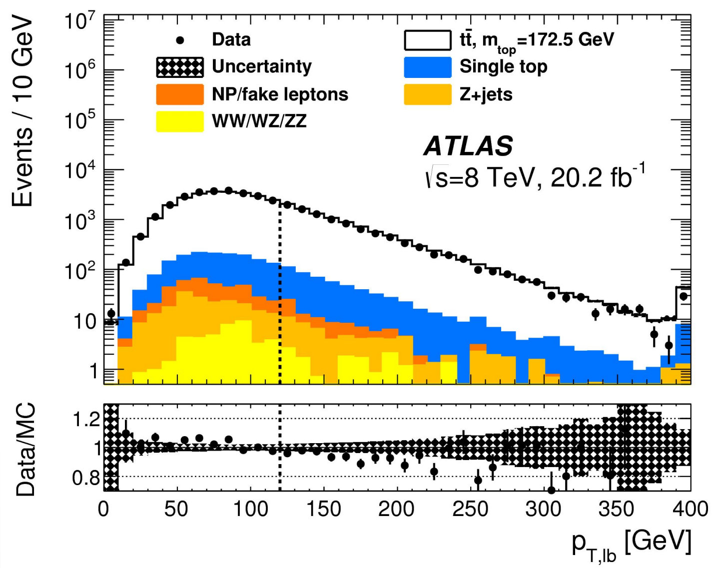
Total Uncertainty:

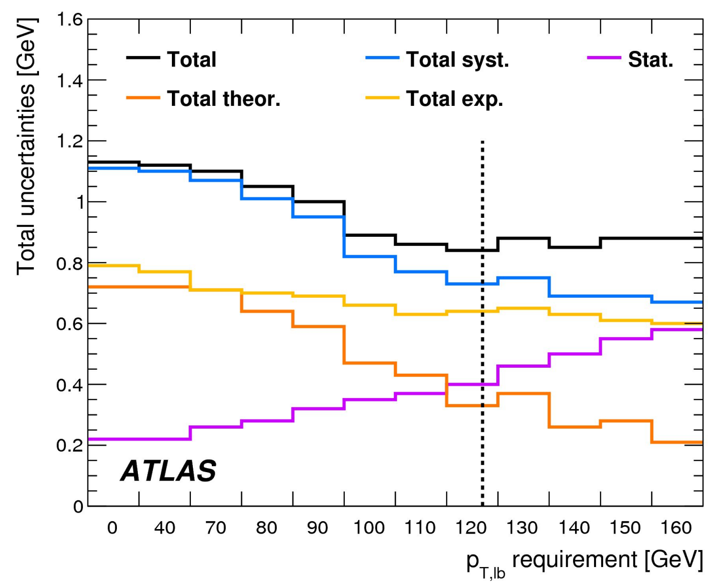
± 0.84 GeV (0.48%)

- Also measured at E_{cm} = 7 TeV: Eur. Phys. J. C (2015) 75:330

Dilepton channel at 8 TeV

- Optimization of systematic (and statistical) uncertainties
- An additional cut on a minimal average $p_{T,lb}$ of the two lepton–b-jet pairs
  - increases the fraction of correctly reconstructed top quark pairs
  - reduces the number of unmatched or wrongly reconstructed pairs
- A cleaner event reconstruction leads to reduced systematic uncertainties
  - Minimize total uncertainty by scanning the $p_{T,lb}$ cut



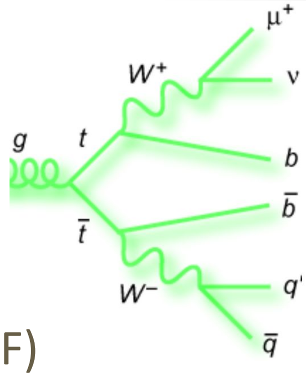


- Most precise measurement in the dilepton channel to date
- Largest uncertainties from (b-)jet energy scales
  - 0.54 and 0.30 GeV

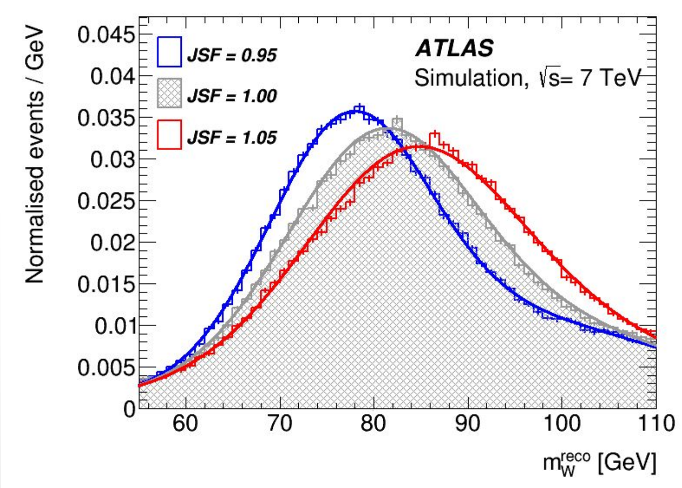
Lepton + jets channel at 7 TeV

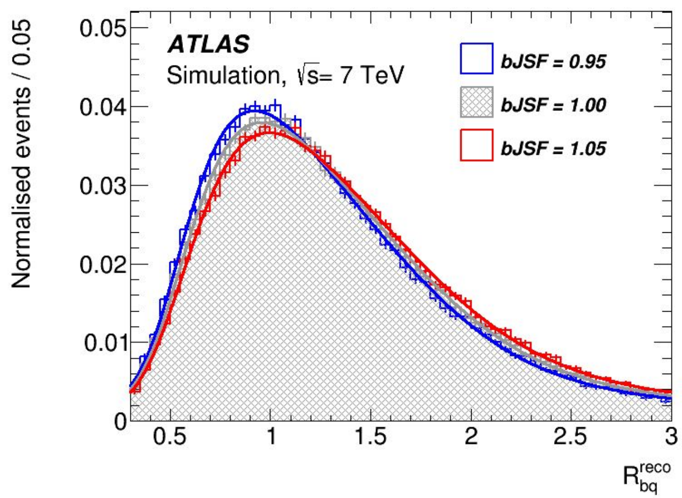
[Eur. Phys. J. C (2015) 75:330]

- Branching ratio ~30%, clean with background O(few %)
- Select events where one W decays leptonically ($e\nu$ or $\mu\nu$)
- Fully reconstruct final state and apply a 3D template method with m_{top}, m_W and R_{bq} as estimators
- In addition to top quark mass, determine a (b-)jet scale factor (JSF)
  - decreases (b-)jet energy scale systematic uncertainties
  - m_W is sensitive estimator to determine JSF
  - The "b to light jet ratio" R_{bq} is used for bJSF



$$R_{bq}^{\mathrm{reco}} = \frac{\sum p_T^{\mathrm{b-tagged\ jets}}}{\sum p_T^{\mathrm{untagged\ jets}}}$$





$$m_{\mathrm{top}}^{\ell+\mathrm{jets}} = 172.33 \pm 0.75\ (\mathrm{stat + JSF + bJSF}) \pm 1.02\ (\mathrm{syst})\ \ \mathrm{GeV}$$

Total Uncertainty:
± 1.26 GeV (0.73%)

- Uncertainties from (b-)jet energy scales: 0.58 and 0.06 GeV

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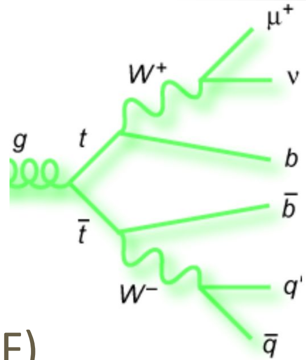
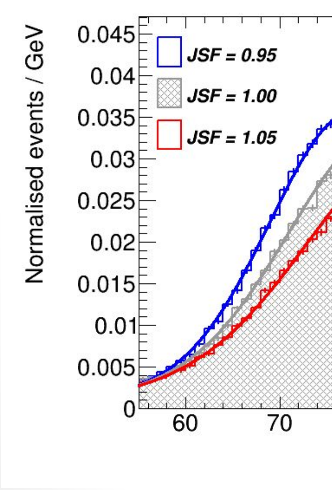
Lepton + jets channel at 7 TeV

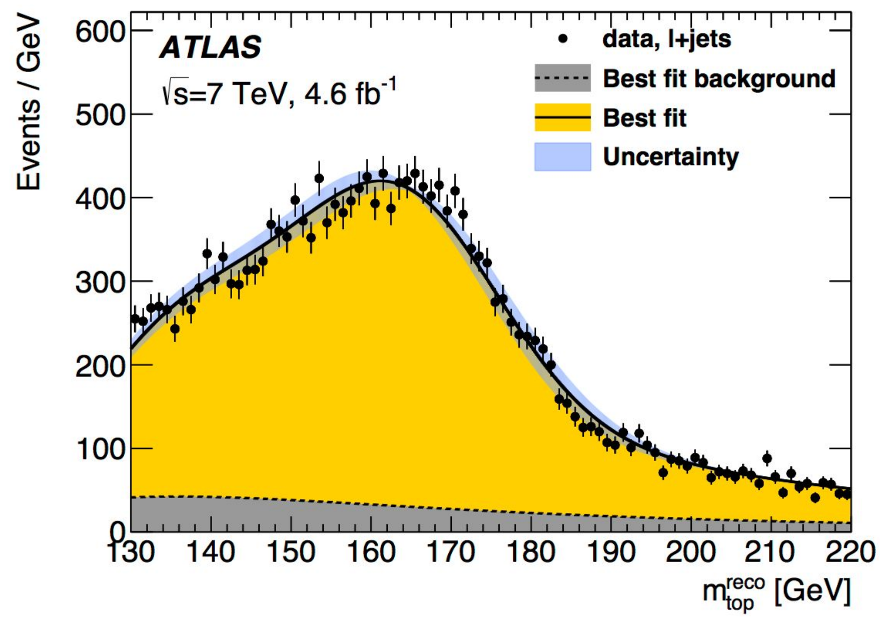
Eur. Phys. J. C (2015) 75:330

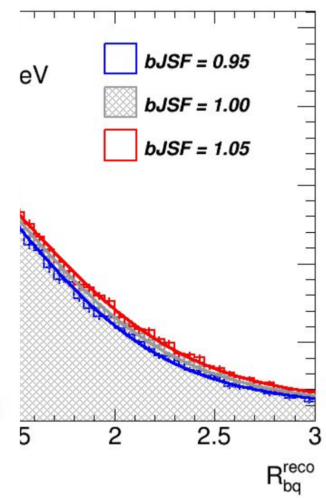


- Branching ratio ~30%, clean with background O(few %)
- Select events where one W decays leptonically ($e\nu$ or $\mu\nu$)
- Fully reconstruct final state and apply a 3D template method with m_{top}, m_W and R_{bq} as top quark mass dependent estimators
- In addition to top quark mass, determine a (b-)jet scale factor (JSF)
  - decreases (b-)jet energy scale systematic uncertainties
  - m_W is se
  - The “b t

$$\frac{\sum p_T^{\mathrm{b-tagged\ jets}}}{\sum p_T^{\mathrm{untagged\ jets}}}$$







$$m_{\mathrm{top}}^{\ell+\mathrm{jets}} = 172.33 \pm 0.75\ (\mathrm{stat} + \mathrm{JSF} + \mathrm{bJSF}) \pm 1.02\ (\mathrm{syst})\ \ \mathrm{GeV}$$

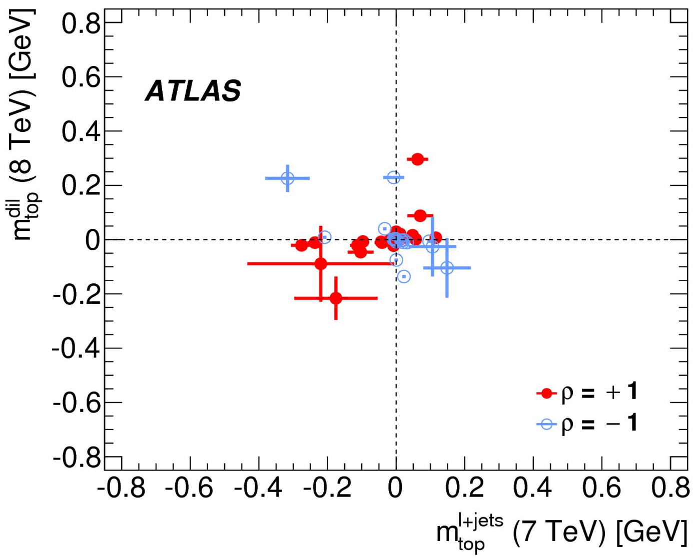
Total Uncertainty:
± 1.26 GeV (0.73%)

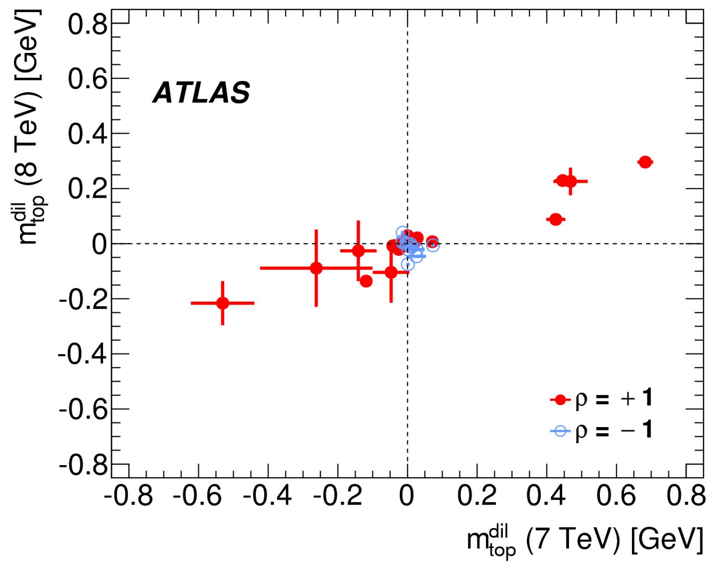
- Uncertainties from (b-)jet energy scales: 0.58 and 0.06 GeV

Combination 2016

arXiv:1606.02179

- Top quark mass measurements in the dilepton channel at E_{cm} = 7-8 TeV and the lepton+jets channel at E_{cm} = 7 TeV have been combined
- Combination is performed using the "Best Linear Unbiased Estimate" (BLUE) method - webpage





- The uncertainty components determine the corresponding correlation between the impact on the measurements (± 1)
- Dilepton and lepton + jets analyses use different methods
  - this leads to smaller correlations compared to dilepton at E_{cm} = 7 and 8 TeV which use identical methods

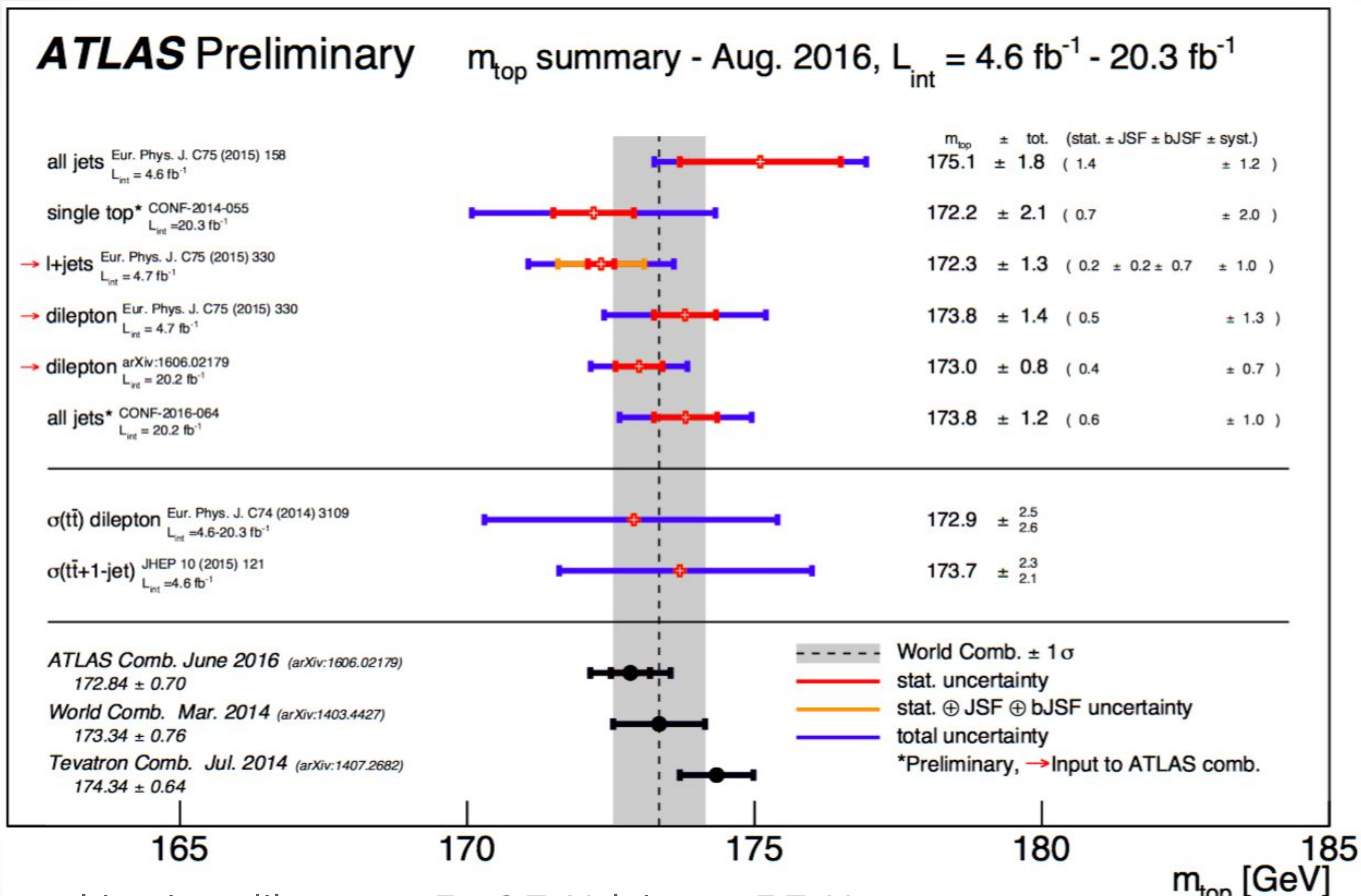
Combination 2016

- Table shows the single input measurements, the determined correlations per uncertainty component and the result of the respective combinations
- Combinations:
  - dilepton and lepton+jets at 7 TeV; dilepton at 7 and 8 TeV; all

	$\sqrt{s}=7$ TeV		$\sqrt{s}=8$ TeV	Correlations			Combinations		
	$m_{top}^{\ell+jets}$ [GeV]	m_{top}^{dil} [GeV]	m_{top}^{dil} [GeV]	ρ_{01}	ρ_{02}	ρ_{12}	$m_{top}^{7\ TeV}$ [GeV]	m_{top}^{dil} [GeV]	m_{top}^{all} [GeV]
Results	172.33	173.79	172.99				172.99	173.04	172.84
Statistics	0.75	0.54	0.41	0	0	0	0.48	0.38	0.34
Method	0.11 ± 0.10	0.09 ± 0.07	0.05 ± 0.07	0	0	0	0.07	0.05	0.05
Signal Monte Carlo generator	0.22 ± 0.21	0.26 ± 0.16	0.09 ± 0.14	+1.00	+1.00	+1.00	0.24	0.10	0.14
Hadronisation	0.18 ± 0.12	0.53 ± 0.09	0.22 ± 0.08	+1.00	+1.00	+1.00	0.34	0.24	0.23
Initial- and final-state QCD radiation	0.32 ± 0.06	0.47 ± 0.05	0.23 ± 0.05	−1.00	−1.00	+1.00	0.04	0.24	0.08
Underlying event	0.15 ± 0.07	0.05 ± 0.05	0.10 ± 0.11	−1.00	−1.00	+1.00	0.06	0.10	0.02
Colour reconnection	0.11 ± 0.07	0.14 ± 0.05	0.03 ± 0.11	−1.00	−1.00	+1.00	0.01	0.03	0.01
Parton distribution function	0.25 ± 0.00	0.11 ± 0.00	0.05 ± 0.00	+0.57	−0.29	+0.03	0.17	0.04	0.08
Background normalisation	0.10 ± 0.00	0.04 ± 0.00	0.03 ± 0.00	+1.00	+0.23	+0.23	0.07	0.03	0.04
W/Z+jets shape	0.29 ± 0.00	0.00 ± 0.00	0	0			0.16	0.00	0.09
Fake leptons shape	0.05 ± 0.00	0.01 ± 0.00	0.08 ± 0.00	+0.23	+0.20	−0.08	0.03	0.07	0.05
Jet energy scale	0.58 ± 0.11	0.75 ± 0.08	0.54 ± 0.04	−0.23	+0.06	+0.35	0.41	0.52	0.41
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.68 ± 0.02	0.30 ± 0.01	+1.00	+1.00	+1.00	0.34	0.32	0.25
Jet energy resolution	0.22 ± 0.11	0.19 ± 0.04	0.09 ± 0.03	−1.00	0	0	0.03	0.08	0.08
Jet reconstruction efficiency	0.12 ± 0.00	0.07 ± 0.00	0.01 ± 0.00	+1.00	+1.00	+1.00	0.10	0.01	0.04
Jet vertex fraction	0.01 ± 0.00	0.00 ± 0.00	0.02 ± 0.00	−1.00	+1.00	−1.00	0.00	0.02	0.02
b-tagging	0.50 ± 0.00	0.07 ± 0.00	0.03 ± 0.02	−0.77	0	0	0.25	0.03	0.15
Leptons	0.04 ± 0.00	0.13 ± 0.00	0.14 ± 0.00	−0.34	−0.52	+0.96	0.05	0.14	0.09
E_T^{miss}	0.15 ± 0.04	0.04 ± 0.03	0.01 ± 0.01	−0.15	+0.25	−0.24	0.08	0.01	0.05
Pile-up	0.02 ± 0.01	0.01 ± 0.00	0.05 ± 0.01	0	0	0	0.01	0.05	0.03
Total systematic uncertainty	1.03 ± 0.31	1.31 ± 0.23	0.74 ± 0.25				0.77	0.74	0.61
Total	1.27 ± 0.33	1.41 ± 0.24	0.84 ± 0.25	−0.07	0.00	0.51	0.91	0.84	0.70

combination: successive reduction of total uncertainty

Combination - Summary



New combination: dilepton at 7 + 8 TeV, l+jets at 7 TeV

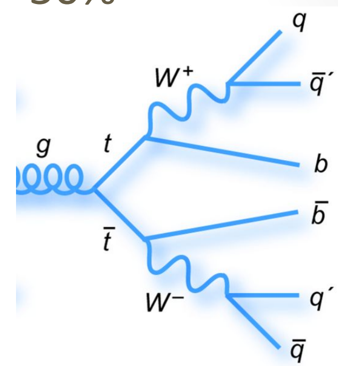
$$m_{\text{top}} = 172.84 \pm 0.34\,(\text{stat}) \pm 0.61\,(\text{syst})\ \text{GeV}$$

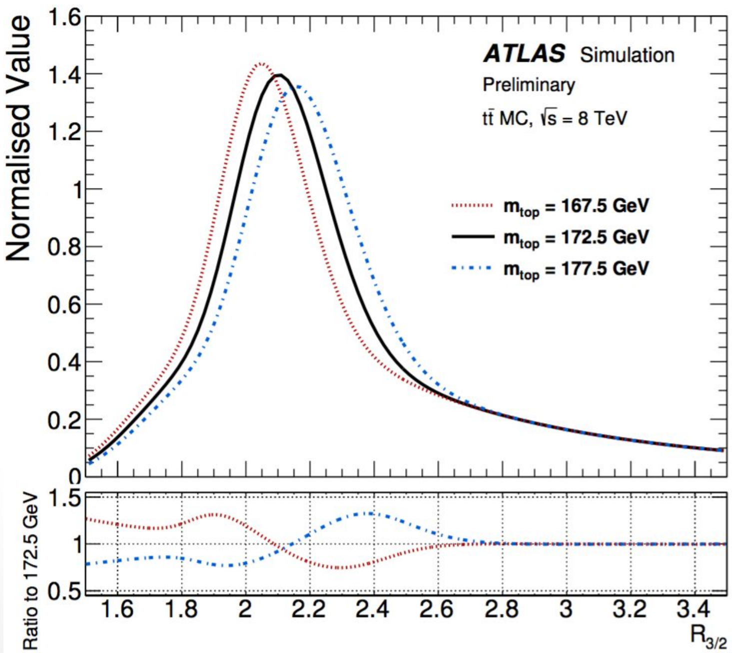
Total Uncertainty:

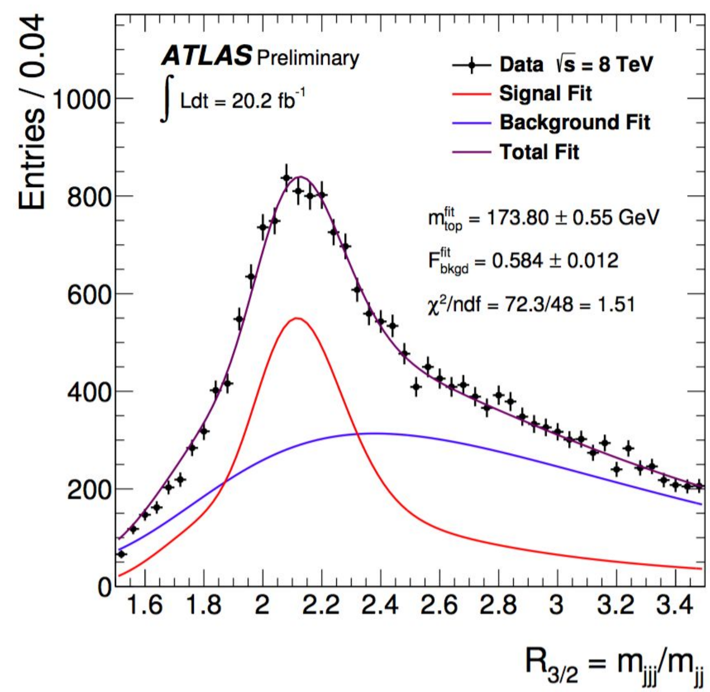
± 0.70 GeV (0.40%)

All hadronic channel at 8 TeV

- High branching ratio 46%, very large QCD initiated background: ~50%
  - Large background is estimated from data (ABCD method)
- Select events where both W's decay hadronically
  - The final state can be fully reconstructed
- Use $R_{3/2} = m_{jjj}/m_{jj}$ as top quark mass dependent estimator
  - ratio reduces depence on jet energy calibration







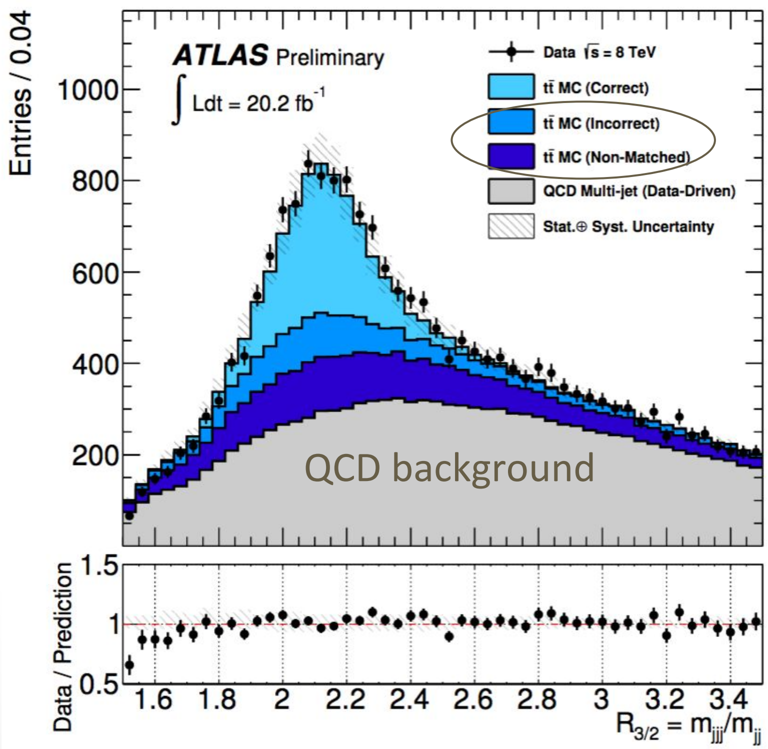
$$m_{top} = 173.80 \pm 0.55\ (\text{stat.}) \pm 1.01\ (\text{syst.})\ \text{GeV}$$

Total Uncertainty:

± 1.15 GeV (0.7%)

All hadronic channel at 8 TeV

- Six jets in final state → combinatorial bkg. due to wrong jet parton assignment
  - Reduce combinatorial background by computing m_{jj} and m_{jjj} for all permutations and minimising a χ^2 function



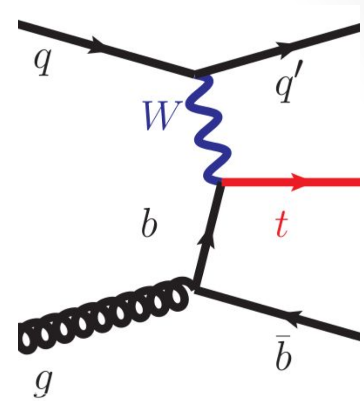
Uncertainty	Δm_{top} [GeV]
Monte Carlo Generator	0.18 ± 0.21
Hadronisation Modelling	0.64 ± 0.15
Parton Distribution Functions	0.04 ± 0.00
Initial/Final-State Radiation	0.10 ± 0.28
Underlying Event	0.13 ± 0.16
Colour Reconnection	0.12 ± 0.16
Template Method Non-Closure	0.06
Signal and Bkgd Parameterisation	0.09
Non All-Hadronic $t\bar{t}$ Contribution	0.06
ABCD *vs.* ABCDEF	0.16
Trigger Efficiency	0.08 ± 0.01
Pile-Up Reweighting	0.01 ± 0.00
Lepton/E_T^{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
Jet Reconstruction Efficiency	0.00 ± 0.00
Total Systematic	1.01
Total Statistical	0.55
Total	1.15

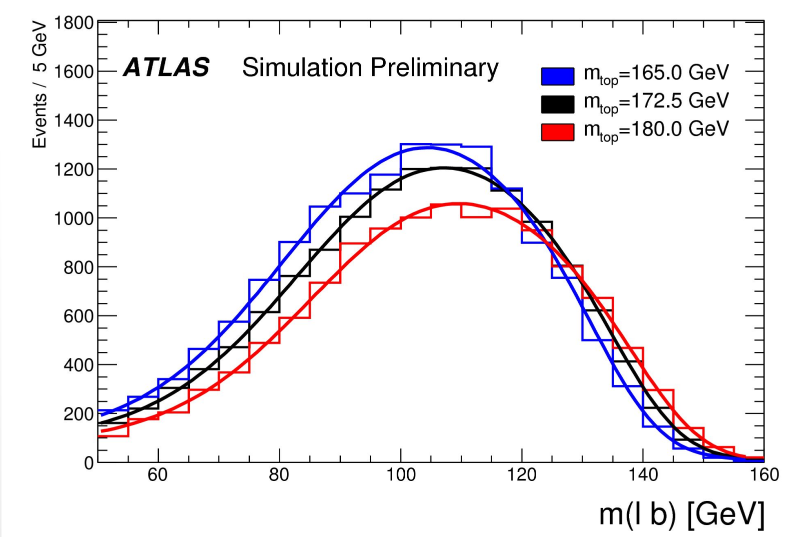
- Largest uncertainties due to jet energy scale and hadronisation

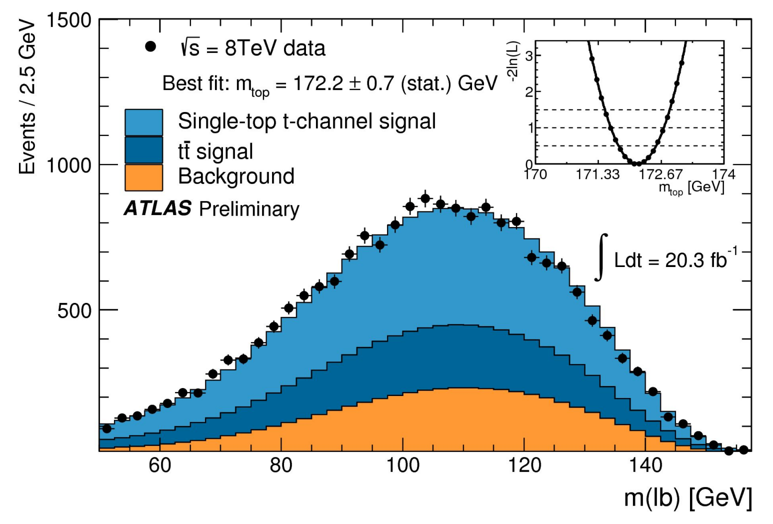
Single Top t-channel at 8 TeV

ATLAS-CONF-2014-055

- Use single top t-channel to measure top quark mass
- Select events where W decays leptonically ($e\nu$ or $\mu\nu$)
- Main background from top pair production and W + jets
  - Reduce background to <30% by use of neural network
- Use invariant mass of lepton b-jet system as estimator
- Largest uncertainty from
  - jet energy calibration: 1.5 GeV, hadronisation: 0.7 GeV







$$m_{\text{top}} = 172.2 \pm 0.7\,(\text{stat.}) \pm 2.0\,(\text{syst.})\ \text{GeV}$$

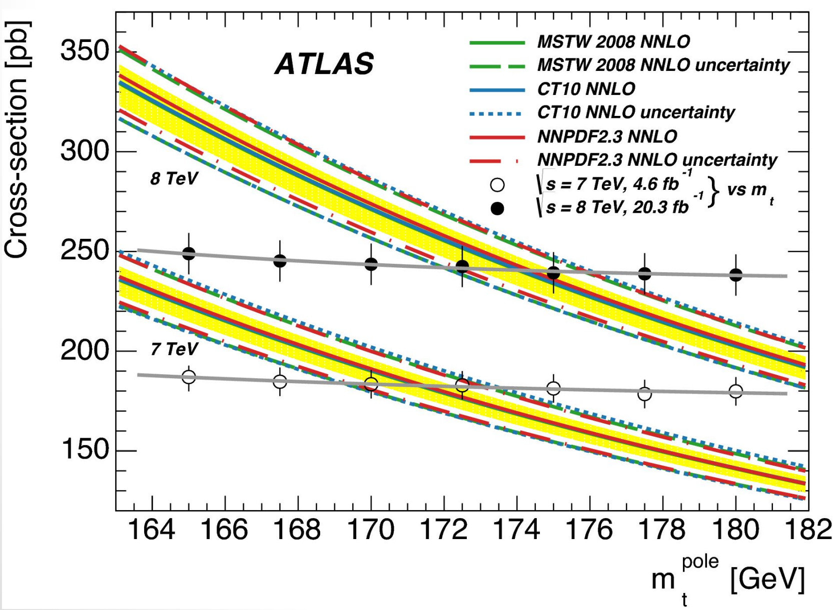
Total Uncertainty:

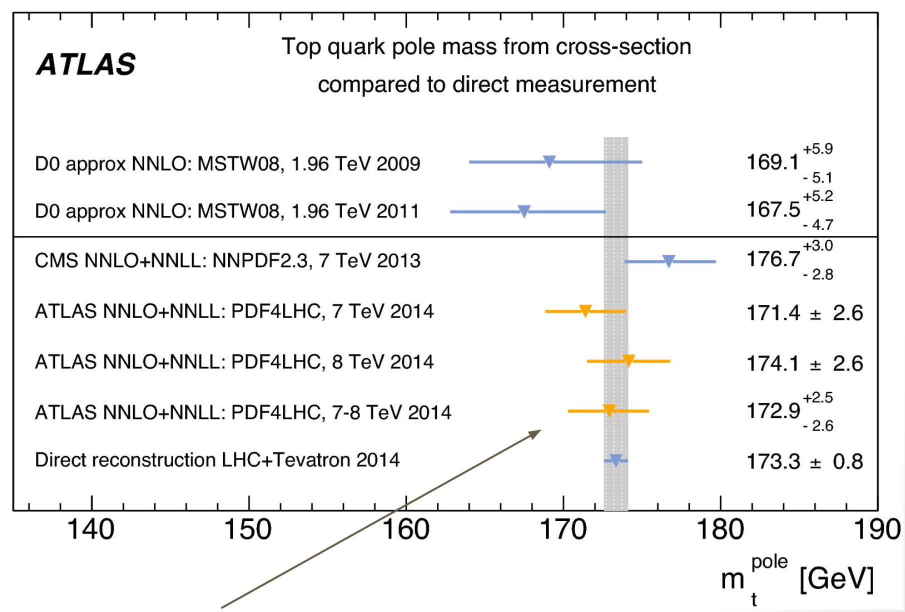
± 2.12 GeV (1.2%)

Top Quark Pole Mass via Cross Section

- The top quark pair production cross section depends on the top quark pole mass: $\sigma_{tt}(m_{t,pole})$
  - measure the cross section and extract the mass
- σ is measured in dilepton final state with opposite-charge eμ pairs
- Largest systematic uncertainties due to
  - particle distribution function: 1.7 GeV
    - baseline PDF is CT10, with PDF4LHC approach to derive systematic unc.
    - uncertainty could be reduced by using more recent PDF sets
  - uncertainty on integrated luminosity itself: 1.8% (2.8%) at E_{cm} = 7 (8) TeV
    - leads to 0.7 (1.2) GeV uncertainty on m_{top} at E_{cm} = 7 (8) TeV

[Eur.Phys.J. C74 (2014) 3109]





error bars include statistical and systematic errors

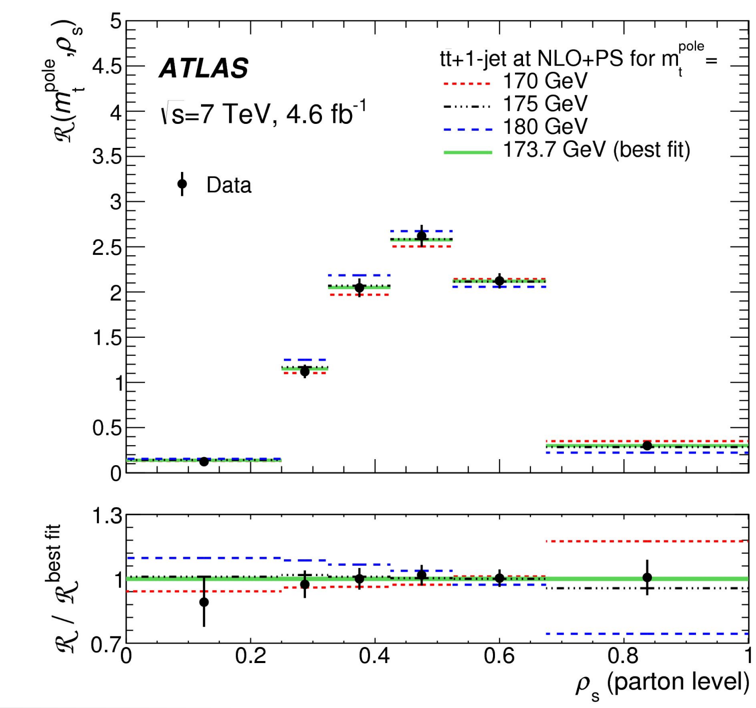
Top Quark Pole Mass - tt + 1 jet

JHEP 10 (2015) 121

- Select top quark pair events in the lepton + jets channel
- Study events of top quark pairs with at least one additional jet
- Normalized differential cross section of tt + 1 jet system

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s) \qquad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

- is sensitive to top quark pole mass



Largest uncertainties from
Statistical: 1.50 GeV
Jet energy scale: 0.96 GeV
Theory (scale variation, PDF): 0.5 - 1.0 GeV

$$m_t^{\text{pole}} = 173.7 \pm 1.5\ (\text{stat.}) \pm 1.4\ (\text{syst.})^{+1.0}_{-0.5}\ (\text{theory})\ \text{GeV}$$

Total Uncertainty:
± 2.1 GeV (2.7%)

Measurement is currently repeated at E_{cm} = 8 TeV

Summary and Outlook

- The top quark mass is a free parameter of the Standard Model
- Precise measurements of the top quark mass are of great importance for theoretical predictions in conjuntion with the Higgs Boson and beyond
- ATLAS has measured the mass at E_{cm} = 8 TeV
  - directly in the dilepton and all hadronic top quark pair production channels
  - directly in the single top t-channel
  - indirectly via cross section measurements
- At E_{cm} = 7 TeV, the top quark mass has been measured in all top quark pair production channels and via cross section measurements
- A few more analyses using Run 1 data are in preparation
- The ATLAS collaboration will continue to perform precise measurements of the top quark mass at E_{cm} = 13 TeV