New results on top-quark mass in ATLAS

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On behalf of:
The ATLAS Collaboration

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Outline

Introduction

Top-quark mass measurements

- Dilepton channel
- All-hadronic channel

Summary

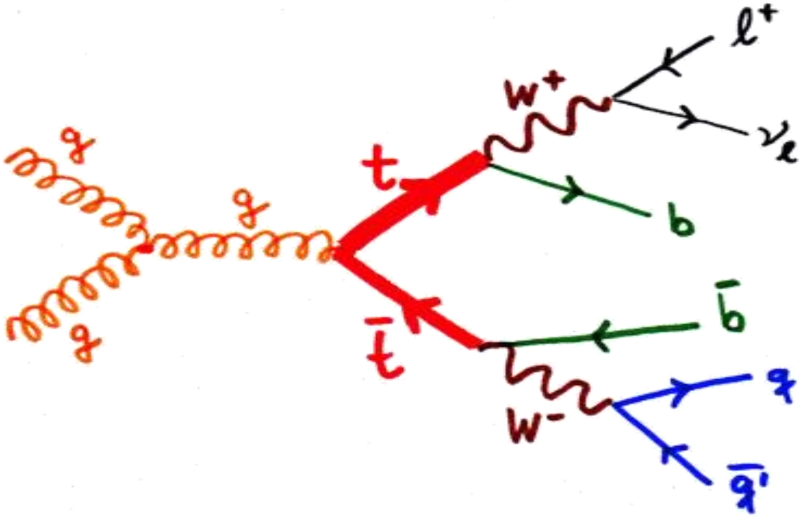
Introduction

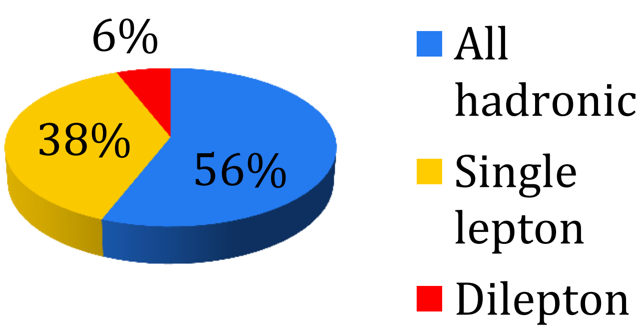
Why should we measure the top-quark mass?

- It is a free parameter of the Standard Model (SM)
  - Produces a significant contribution to electroweak radiative corrections
  - A precise measurement is important for many models of physics beyond the SM
- Its value is important for the consistency of the SM

Experimental measurements in $t\bar{t}$

- Traditionally measured in the single lepton channel
- The dilepton and all-hadronic channels are also competitive
- Most precise measurements are for the "Monte-Carlo mass"



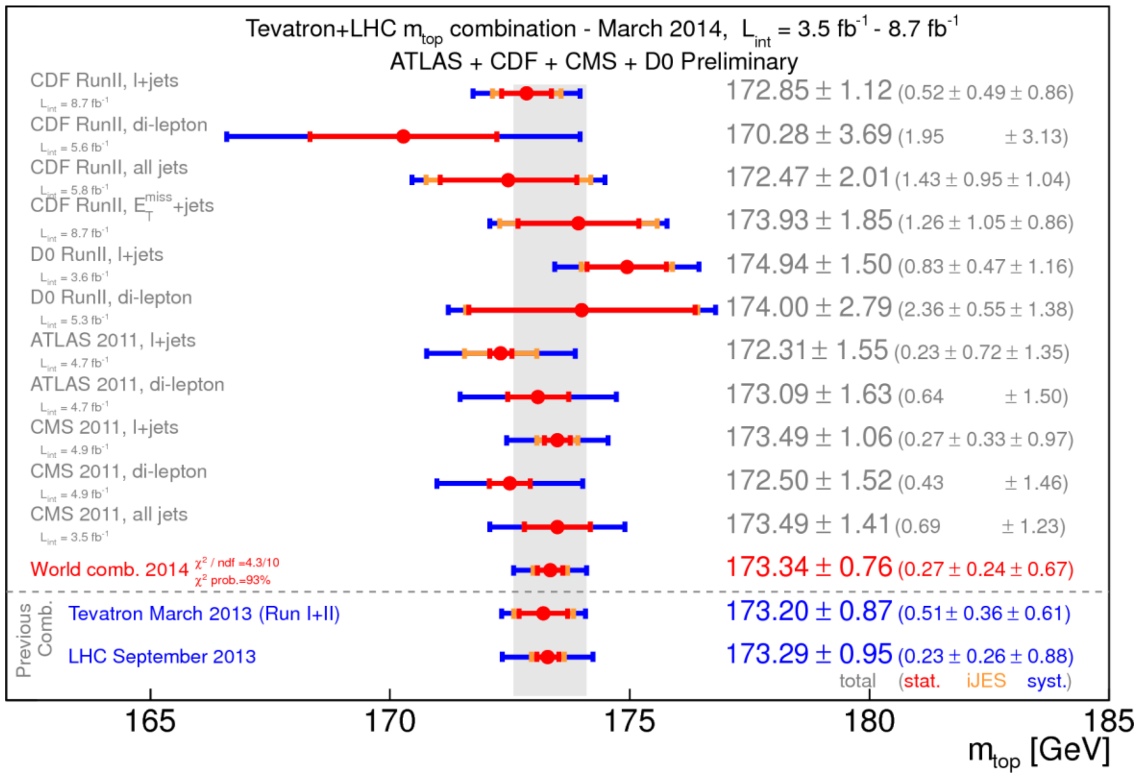


$\ell = e, \mu, \tau_{\text{lep}}$

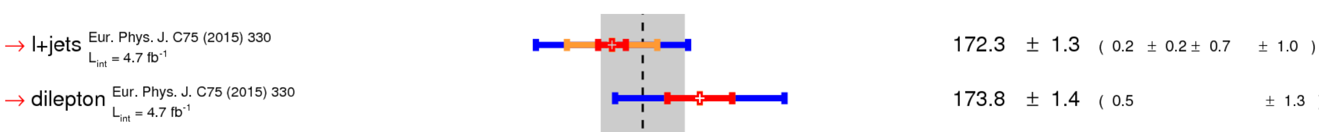
Introduction

Earlier top-quark mass measurements:

- LHC+Tevatron combination in 2014

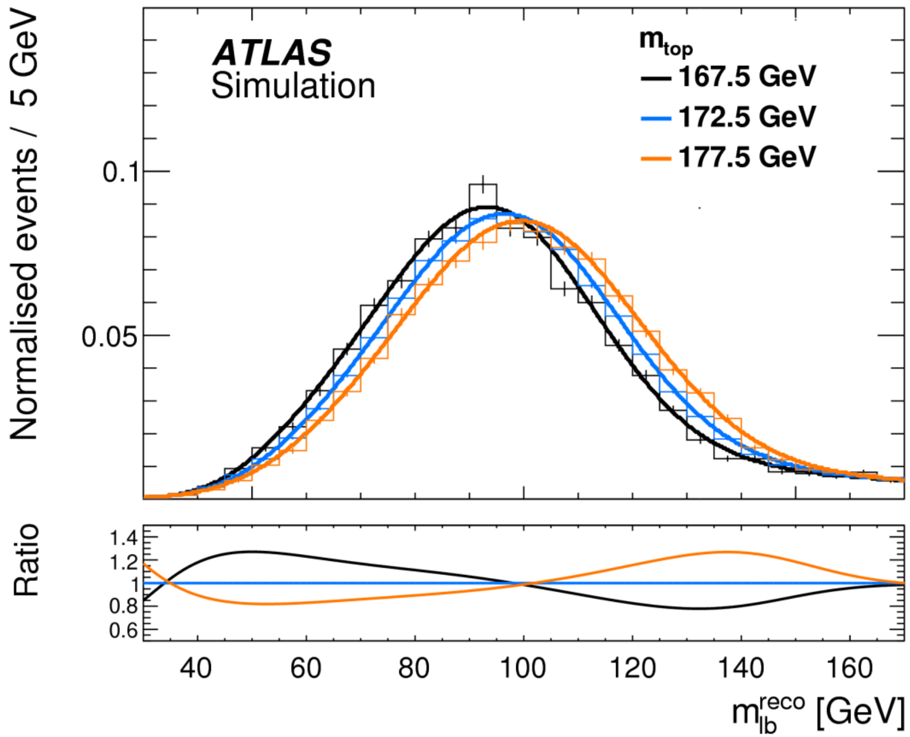


- Two ATLAS measurements in 2015 (7 TeV)



Template method

- Determine an observable that depends on the top-quark mass
- Model the distribution of this observable as a function of the top-quark mass with the help of Monte Carlo simulations
- Use this template to fit the data and measure the top-quark mass



Dilepton channel

Dilepton channel

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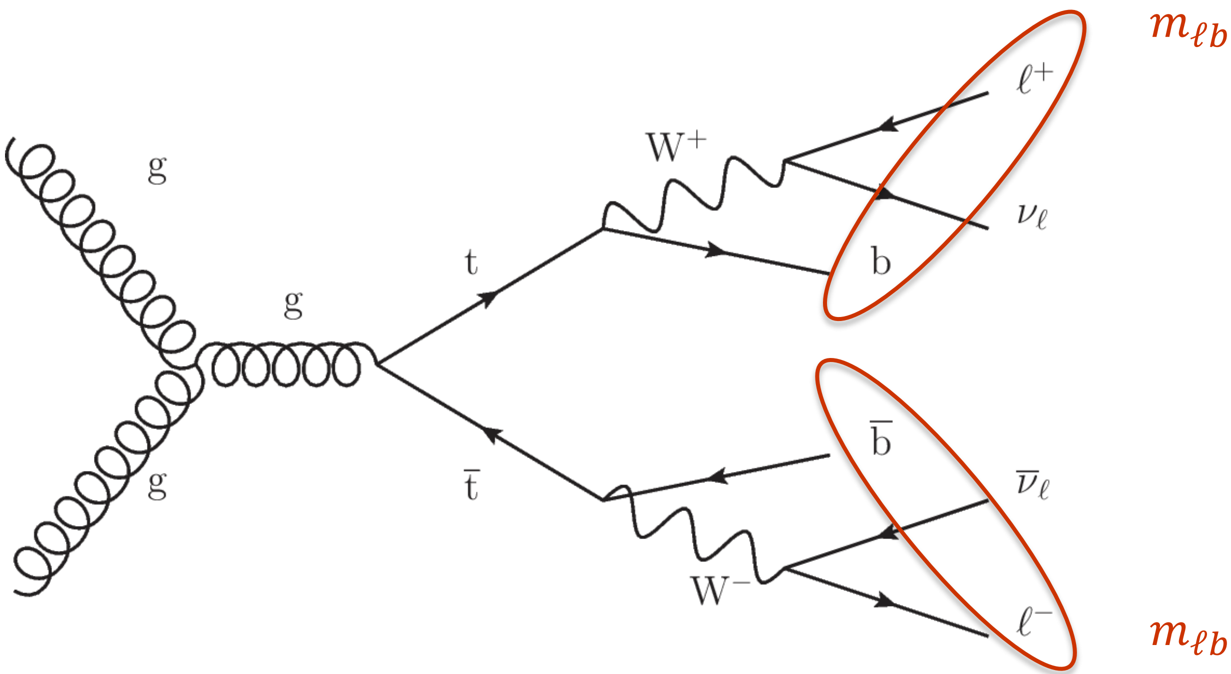
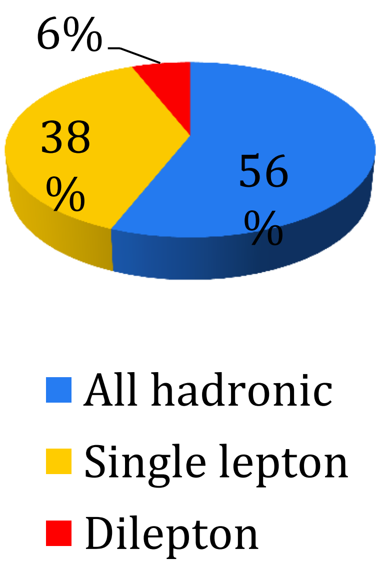
Using the template method:

- Data: 20.2 fb^{-1}, $\sqrt{s} = 8$ TeV
- Signal MC: Powheg-Box Pythia6 with P2011C tune and CTEQ6L1 PDF

Chosen observable: $m_{\ell b}$

- Defined as the average invariant masses of the lepton-*b*-jet systems





Dilepton channel

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Event preselection:

- Exactly two opposite-sign reconstructed leptons with $p_{\mathrm{T}} > 25$ GeV
- At least one trigger-matched lepton
- At least two reconstructed central jets with $p_{\mathrm{T}} > 25$ GeV
- At least one of the reconstructed jets must be b-tagged (70% efficiency)
- For the ee and $\mu\mu$ channels:
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV
  - $m_{\ell\ell} > 15$ GeV
  - $|m_{\ell\ell} - m_Z| > 10$ GeV
- For the $e\mu$ channel:
  - The scalar sum of the transverse momentum of all reconstructed jets and leptons (H_{T}) must be larger than 130 GeV

Dilepton channel

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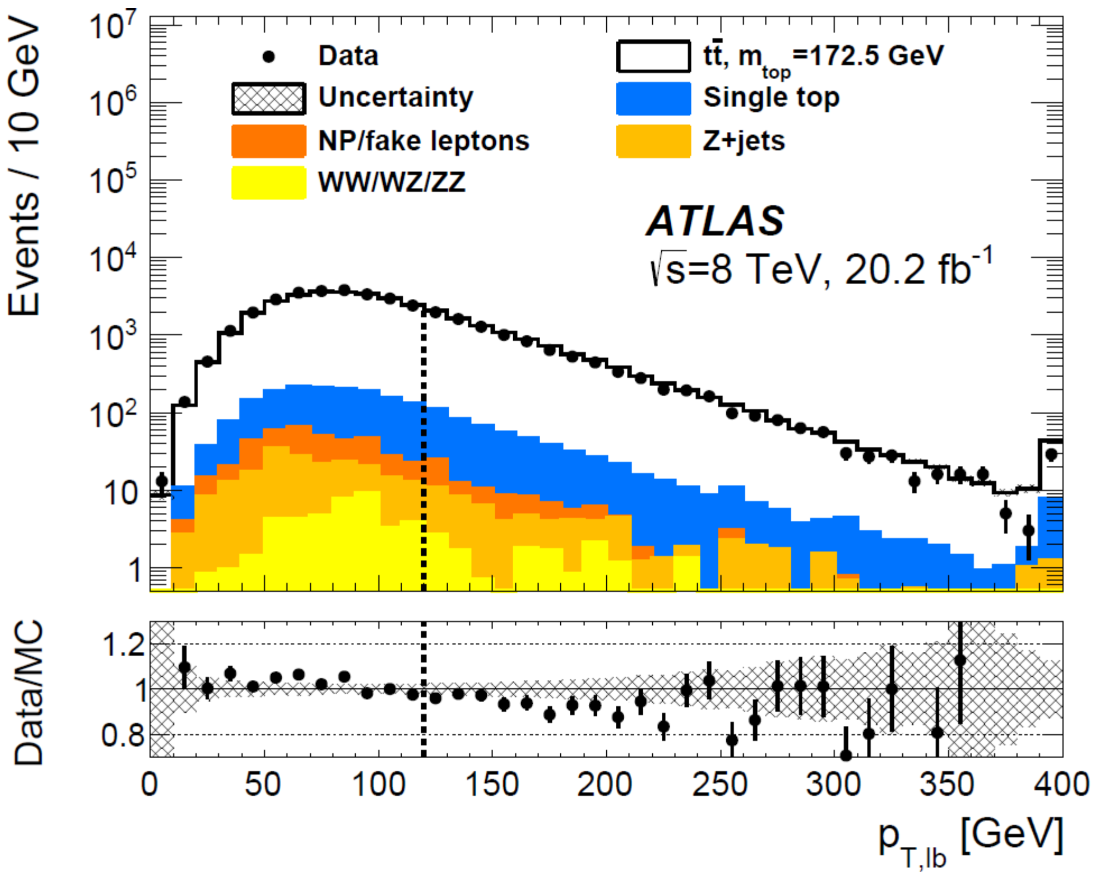
Additional cuts:

- The average transverse momentum of the two lepton-b-jet pairs ($p_{\mathrm{T},\ell b}$) must be larger than 120 GeV
- 30 GeV $< m_{\ell b} <$ 170 GeV



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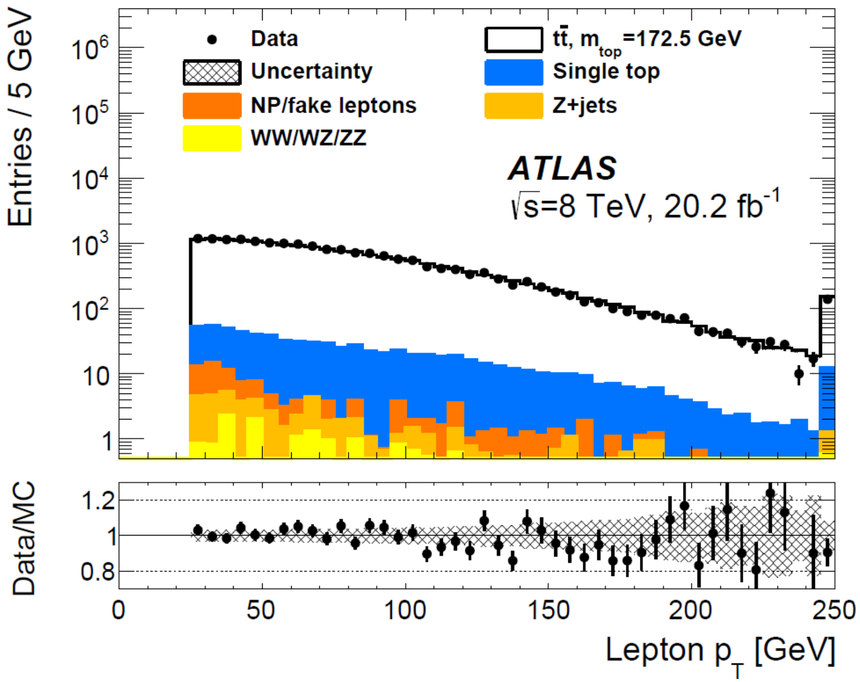
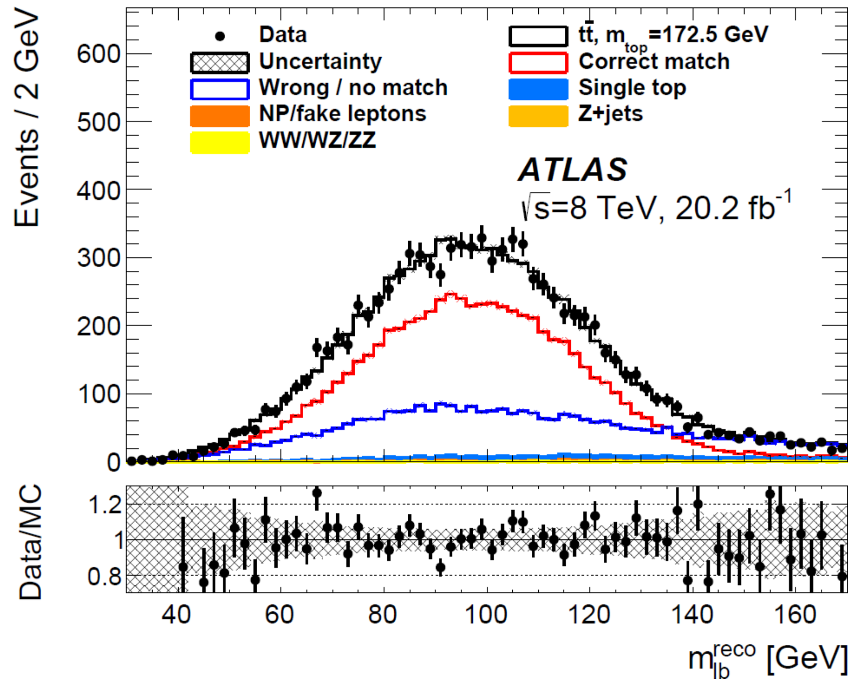
Final selection:





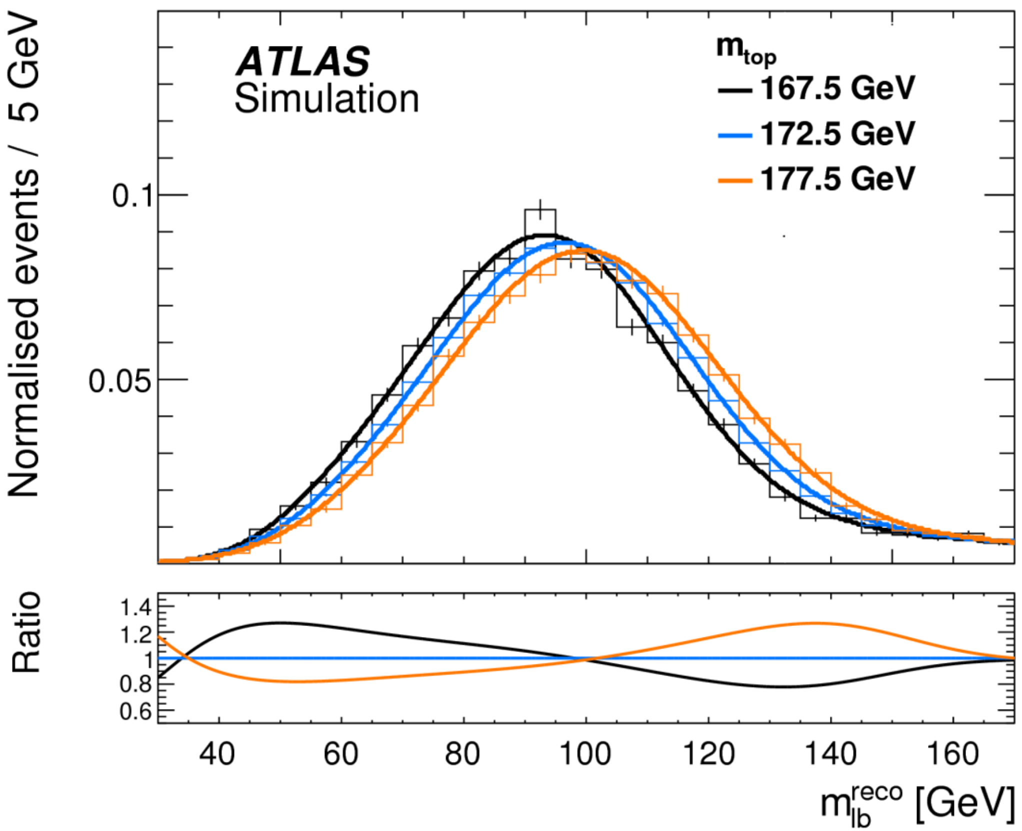
Event yields:

Selection	Pre-selection	Final selection
$t\bar{t}$ signal	34300 ± 2700	9670 ± 770
Single-top-quark signal	1690 ± 110	363 ± 23
Fake leptons	240 ± 240	31 ± 31
Z+jets	212 ± 83	20.6 ± 8.5
$WW/WZ/ZZ$	57 ± 21	10.2 ± 3.8
Signal+background	36600 ± 2800	10100 ± 770
Data	36359	9426
Expected background fraction	0.01 ± 0.01	0.01 ± 0.00
Data / (Signal+background)	0.99 ± 0.07	0.93 ± 0.07
Matching efficiency [%]	78.4 ± 0.2	95.3 ± 0.4
Selection purity [%]	51.6 ± 0.1	69.8 ± 0.3
Unmatched events [%]	34.2 ± 0.1	26.7 ± 0.1
Wrongly matched events [%]	14.2 ± 0.1	3.4 ± 0.0

Dilepton channel

Template used:

- Signal: Gaussian + Landau
- Background: Landau
- Template is parametrised using only the top-quark mass



Dilepton channel

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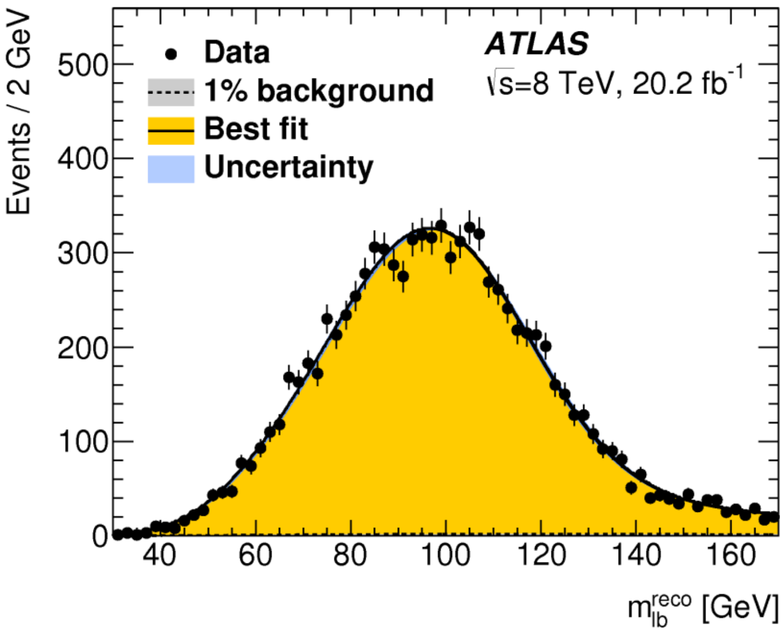
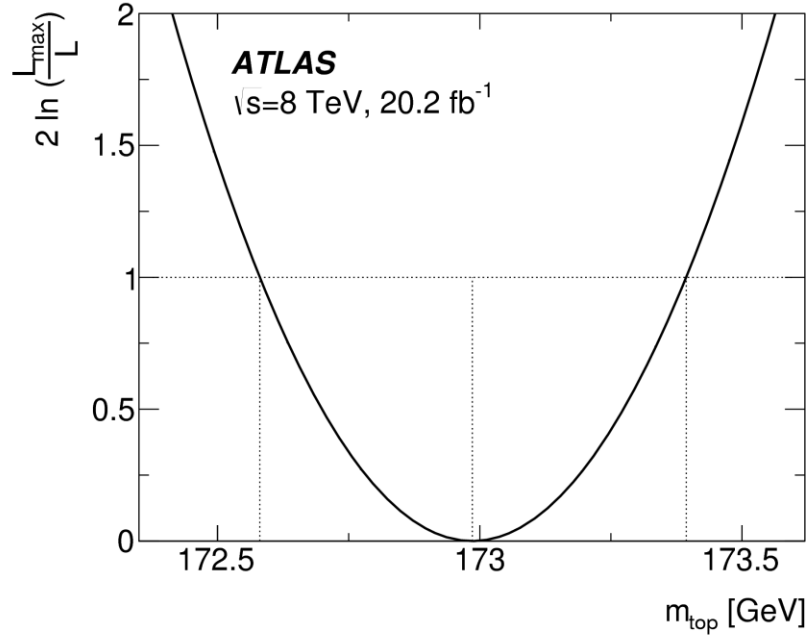
Results:





$$m_{\text{top}} = 172.99 \pm 0.41\ (\text{stat.}) \pm 0.74\ (\text{syst.})\ \text{GeV},\ (\sigma_{\text{total}} = 0.49\%)$$

Most precise measurement of the top-quark mass in the dilepton channel to date!

Dilepton channel

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Uncertainties:

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

Hadronisation: (Powheg-Box) (Pythia6 vs Herwig+Jimmy)
ISR/FSR: Vary Λ_{QCD}, Q^2_{max} and h_{damp}

Dilepton channel

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Combination:

	$\sqrt{s}=7$ 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

$$m_{top} = 172.84 \pm 0.34\ (\text{stat.}) \pm 0.61\ (\text{syst.})\ \text{GeV},\ (\sigma_{total} = 0.40\%)$$

All-hadronic channel

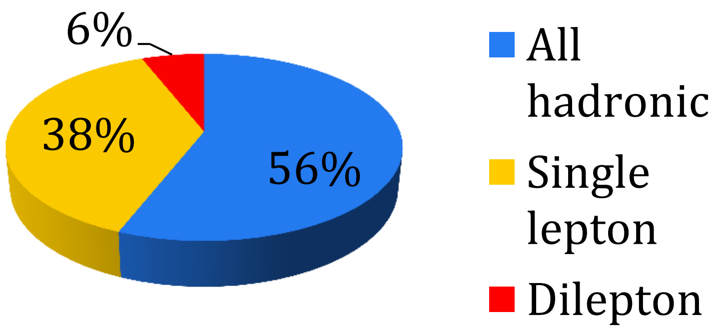
All-hadronic channel

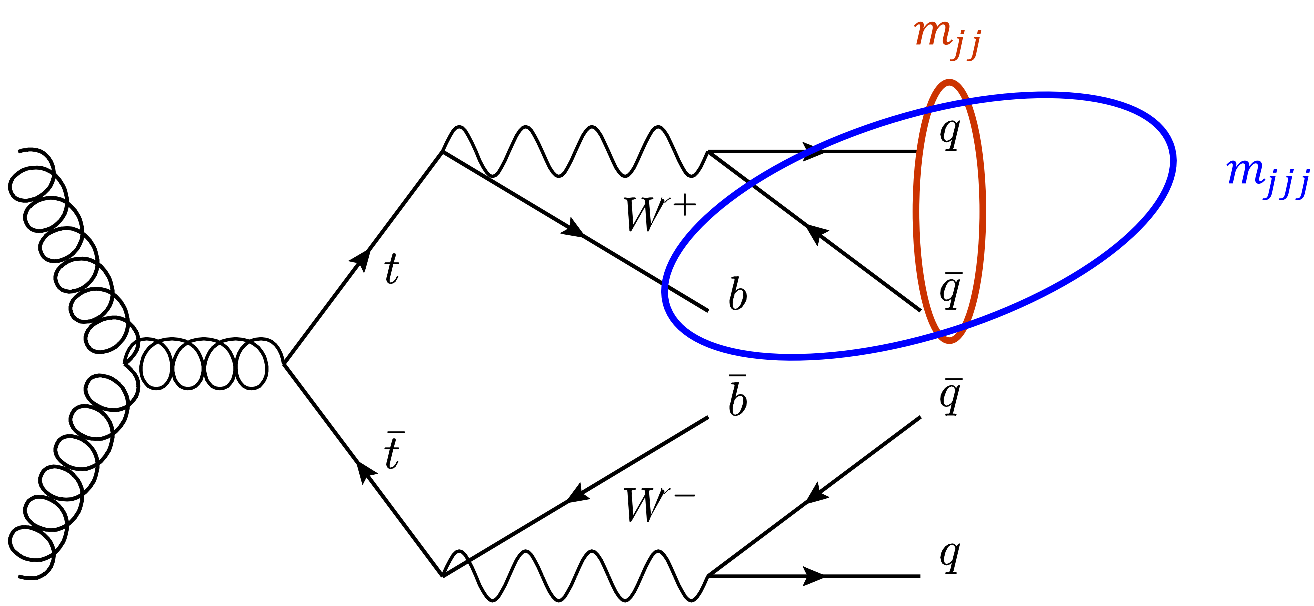
Using the template method:

- Data: 20.2 fb^{-1}, $\sqrt{s} = 8$ TeV
- Signal MC: Powheg-Box Pythia6 with Perugia2012 tune and CT10 PDF

Chosen observable: $R_{3/2}$

- Defined as: $R_{3/2} = \frac{m_{jjj}}{m_{jj}}$ (2 per $t\bar{t}$ event)





All-hadronic channel

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Event selection:

- No reconstructed leptons
- At least 6 reconstructed jets with $p_T > 25$ GeV
- At least 5 reconstructed jets with $p_T > 60$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV
- At least 2 of the 6 leading-p_T jets must be b-tagged (57% efficiency)
- $\Delta\phi(b_1, b_2) > 1.5$
  - b_1, b_2 are the two jets most-likely to have originated from a b-quark

$t\bar{t}$ reconstruction:

$$\chi^2 = \frac{(m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4})^2}{\sigma^2_{\Delta m_{bjj}}} + \frac{(m_{j_1 j_2} - m_W^{\mathrm{MC}})^2}{\sigma^2_{m_W^{\mathrm{MC}}}} + \frac{(m_{j_3 j_4} - m_W^{\mathrm{MC}})^2}{\sigma^2_{m_W^{\mathrm{MC}}}}$$

- $\Delta \mathrm{m_{bjj}} = m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4}$
- $\sigma_{\Delta \mathrm{m_{bjj}}} = 21.60 \pm 0.16\ (\mathrm{stat.})\ \mathrm{GeV}$
- $m_W^{\mathrm{MC}} = 81.18 \pm 0.04\ (\mathrm{stat.})\ \mathrm{GeV}$
- $\sigma_{m_W^{\mathrm{MC}}} = 7.89 \pm 0.05\ (\mathrm{stat.})\ \mathrm{GeV}$
- Try each combination and choose the one with the lowest χ^2

Further event selection requirements:

- $\min(\chi^2) < 11$
- $\Delta\phi(b, W) < 2$
  - $\Delta\phi(b, W)$: average separation of the W-boson candidates and their associated b-tagged jet

All-hadronic channel

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Multi-jet background estimation:

- Estimated using a data-driven method (ABCD method)

ABCD Region and Definition			Estimated Signal Fraction
Region	$N_{b_{\mathrm{tag}}}$	$\langle\Delta\phi(b,W)\rangle$	$t\bar{t}$ MC/data [%]
A	<2	≥ 2.0	2.06 ± 0.02
B	<2	< 2.0	2.60 ± 0.02
C	≥ 2	≥ 2.0	24.71 ± 0.55
D	≥ 2	< 2.0	34.05 ± 0.57

$$N^{\mathrm{SR\ D}}_{\mathrm{background},i} = \left(\frac{N^{\mathrm{CR\ C}}_{\mathrm{background}}}{N^{\mathrm{CR\ A}}_{\mathrm{background}}}\right) N^{\mathrm{CR\ B}}_{\mathrm{background},i}$$

Multi-jet background estimation uncertainty:

- Alternative regions: ABCDEF
  - Regions A, C and E are used to estimate the normalization
  - Regions B and D are used to estimate the shape
  - Region F is the signal region

Region	A	B	C	D	E	F
$N_{b_{\mathrm{tag}}}$	0	0	1	1	≥ 2	≥ 2
$\langle \Delta\phi(b, W) \rangle$	≥ 2	< 2	≥ 2	< 2	≥ 2	< 2

$$N_F^{\mathrm{bkg}}(x) = \frac{N_E^{\mathrm{bkg}}}{2} \cdot \left(\frac{N_B^{\mathrm{bkg}}(x)}{N_A^{\mathrm{bkg}}} + \frac{N_D^{\mathrm{bkg}}(x)}{N_C^{\mathrm{bkg}}} \right)$$

  - The difference between the measured top mass using the ABCD and the ABCDEF methods is 0.16 GeV

All-hadronic channel

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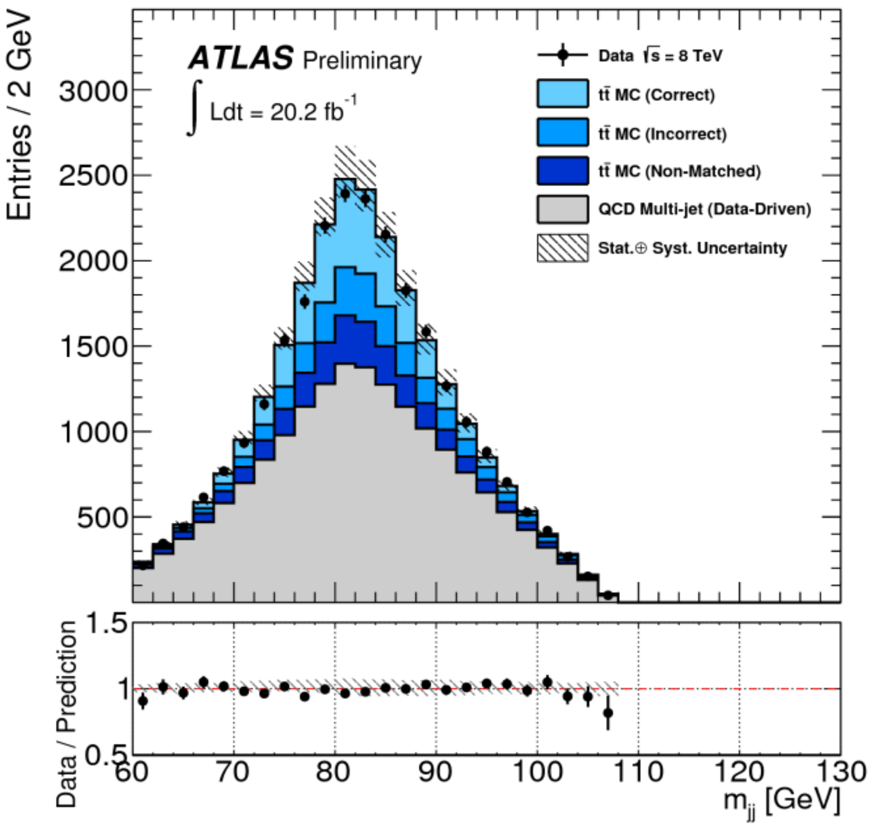

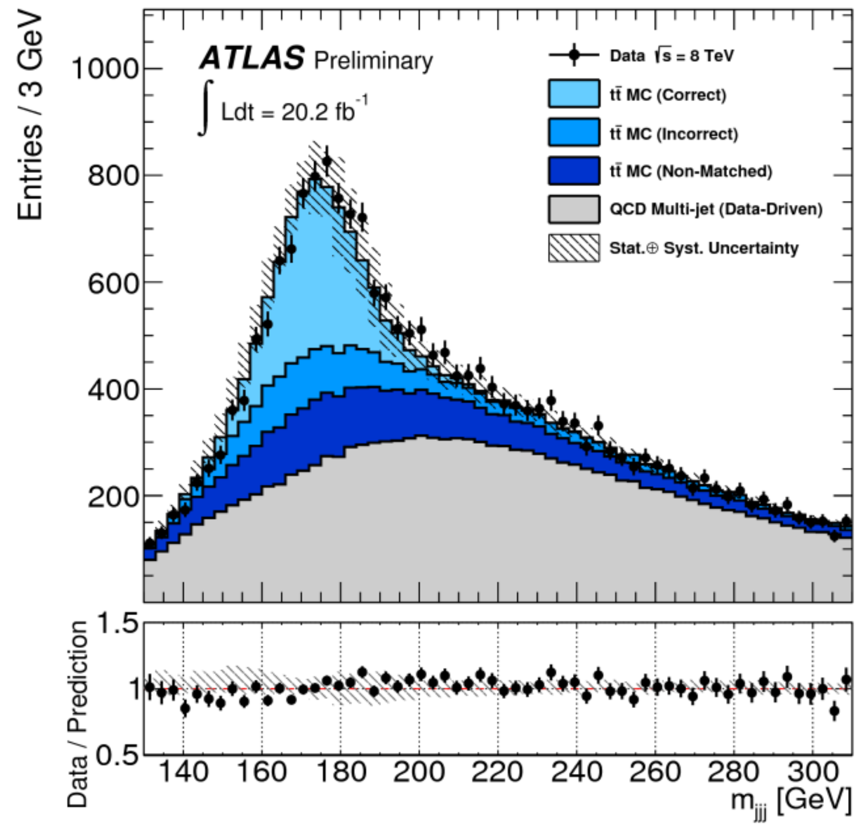

Expected purity: 34%

All-hadronic channel

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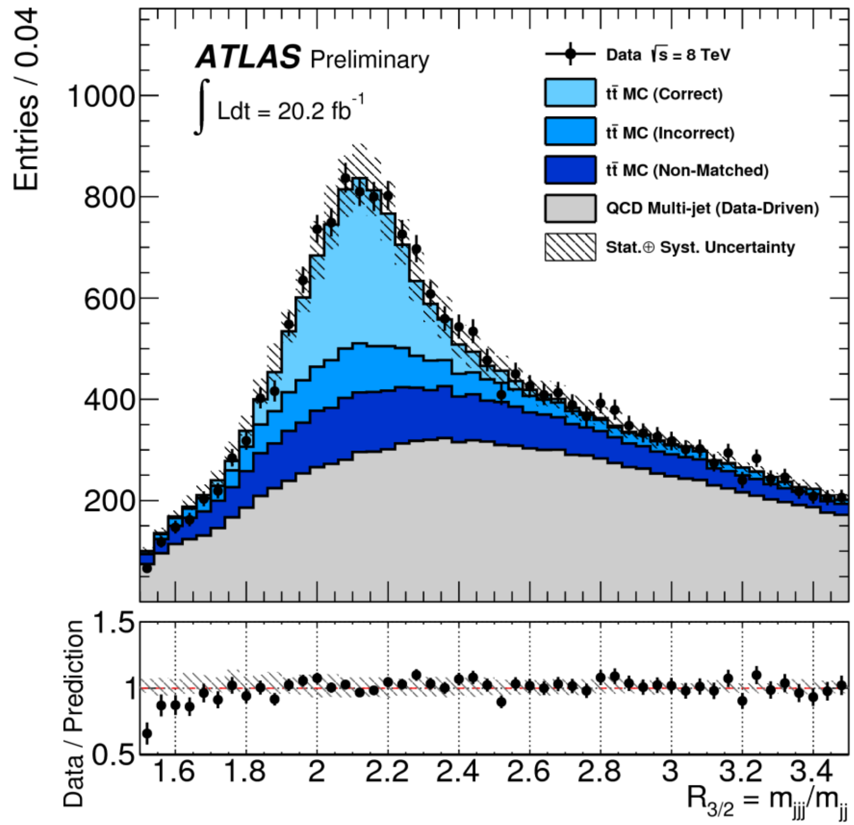
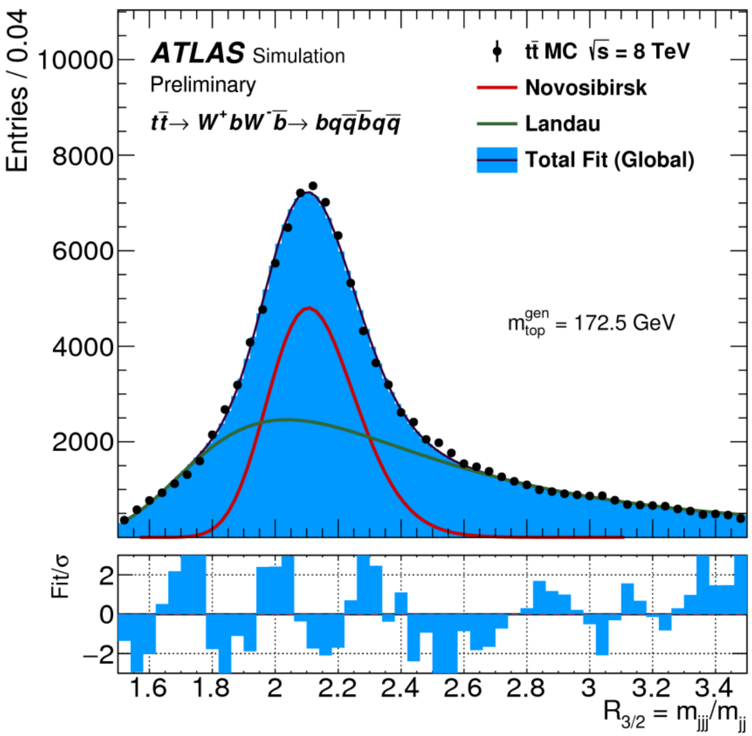


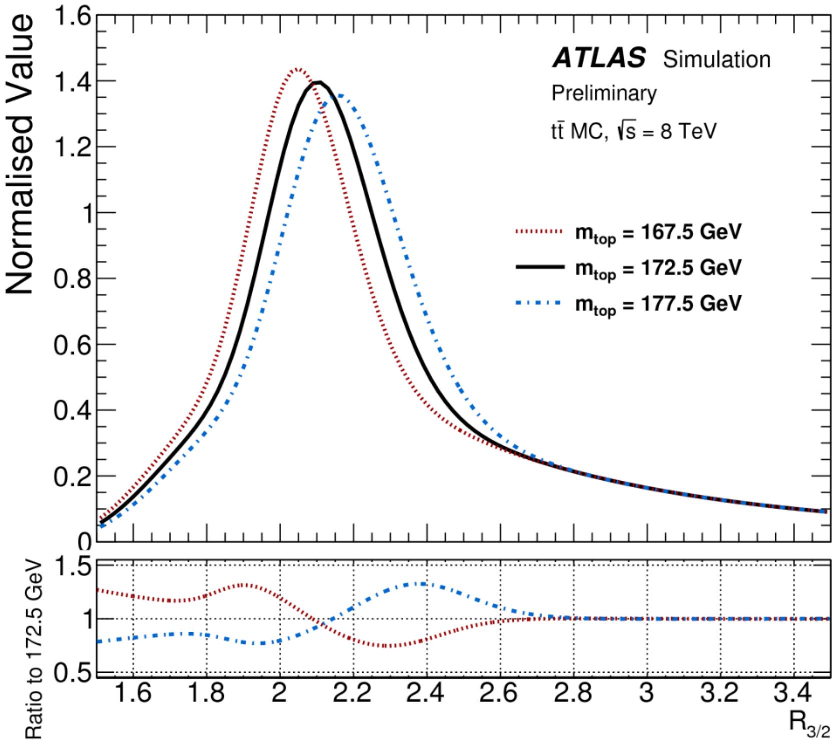
- Two $R_{3/2}$ per event
- Correlation between them: 0.59

All-hadronic channel

Template used:

- Signal: Novosibirsk
- Background: Landau
- Template depends on the top-quark mass and the background fraction parameter (F_{bkgd})





All-hadronic channel

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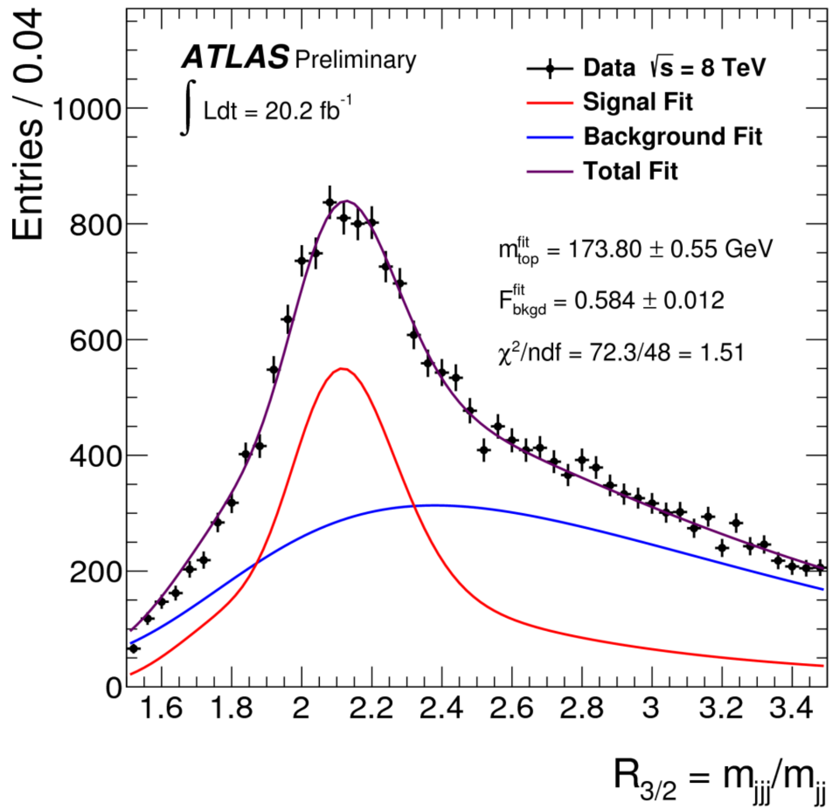
Results:



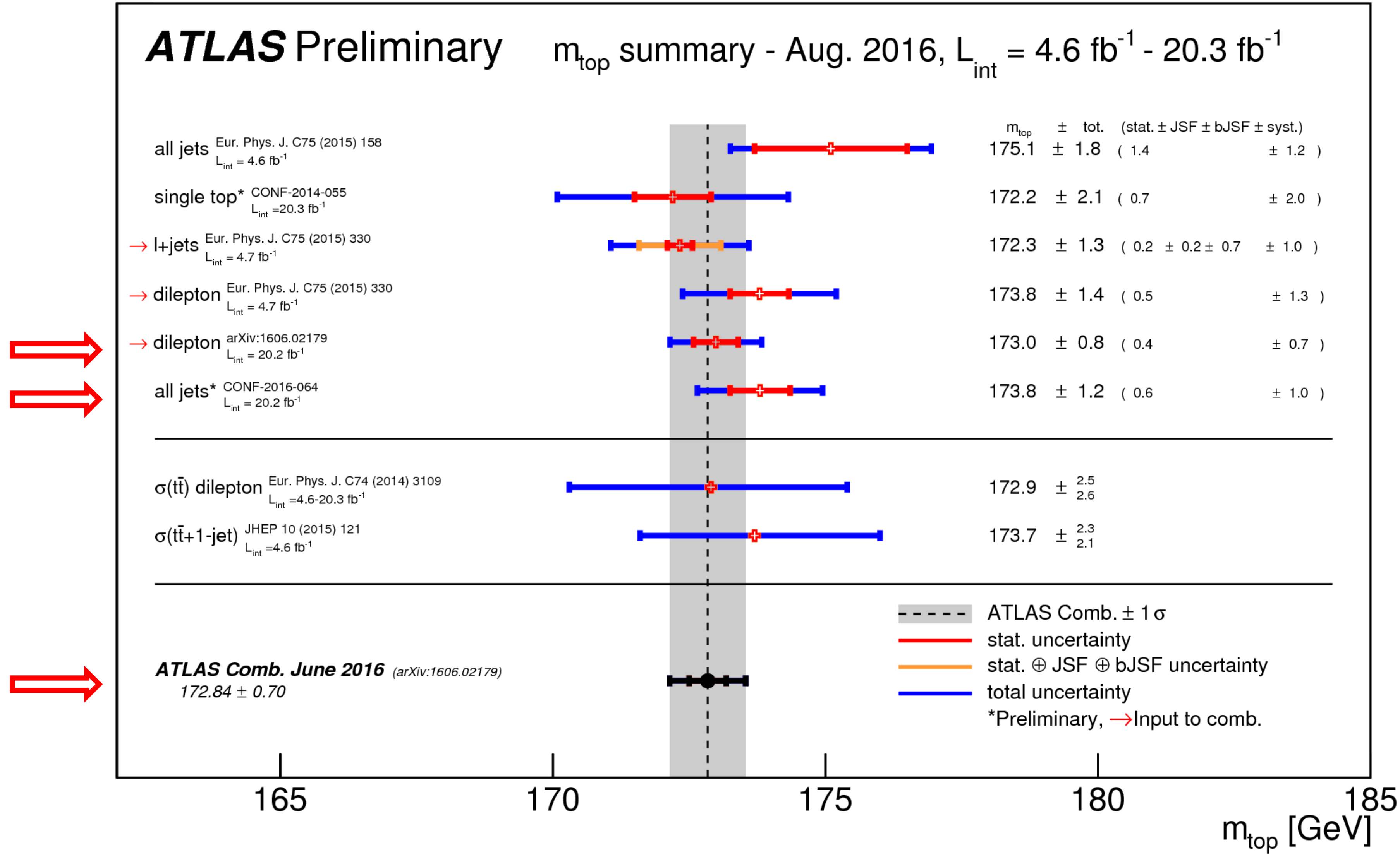
$$m_{\text{top}} = 173.80 \pm 0.55\ (\text{stat.}) \pm 1.01\ (\text{syst.})\ \text{GeV}, (\sigma_{\text{total}} = 0.66\%)$$

Uncertainties:

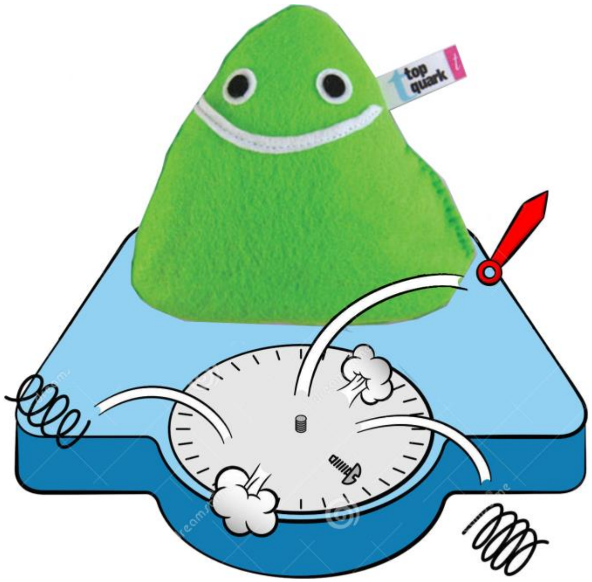
Uncertainty	Δm_{top} [*GeV*]
Monte Carlo generator	0.18 ± 0.21
Hadronisation modelling	0.64 ± 0.15
Parton distribution functions	0.04 ± 0.00
Initial/final-state radiation	0.10 ± 0.28
Underlying event	0.13 ± 0.16
Colour reconnection	0.12 ± 0.16
Bias in template method	0.06
Signal and bkgd parameterisation	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/$E_{\text{T}}^{\text{miss}}$ 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	1.01
Total Statistical	0.55
Total	1.15

Hadronisation: (POWHEG-BOX) (PYTHIA6 vs HERWIG)

Summary


ATLAS Preliminary
m_top summary - Aug. 2016, L_int = 4.6 fb^-1 - 20.3 fb^-1
m_top ± tot. (stat. ± JSF ± bJSF ± syst.)
all jets Eur. Phys. J. C75 (2015) 158 L_int = 4.6 fb^-1
175.1 ± 1.8 (1.4 ± 1.2)
single top* CONF-2014-055 L_int =20.3 fb^-1
172.2 ± 2.1 (0.7 ± 2.0)
l+jets Eur. Phys. J. C75 (2015) 330 L_int = 4.7 fb^-1
172.3 ± 1.3 (0.2 ± 0.2 ± 0.7 ± 1.0)
dilepton Eur. Phys. J. C75 (2015) 330 L_int = 4.7 fb^-1
173.8 ± 1.4 (0.5 ± 1.3)
dilepton arXiv:1606.02179 L_int = 20.2 fb^-1
173.0 ± 0.8 (0.4 ± 0.7)
all jets* CONF-2016-064 L_int = 20.2 fb^-1
173.8 ± 1.2 (0.6 ± 1.0)
σ(tt̄) dilepton Eur. Phys. J. C74 (2014) 3109 L_int =4.6-20.3 fb^-1
172.9 ± 2.5 2.6
σ(tt̄+1-jet) JHEP 10 (2015) 121 L_int =4.6 fb^-1
173.7 ± 2.3 2.1
ATLAS Comb. June 2016 (arXiv:1606.02179)
172.84 ± 0.70
ATLAS Comb. ± 1 σ
stat. uncertainty
stat. ⊕ JSF ⊕ bJSF uncertainty
total uncertainty
*Preliminary, →Input to comb.
165
170
175
180
185
m_top [GeV]

Thank you for your attention!



Backup

Dilepton channel

Trigger:

- Single electron or muon trigger ($p_{\mathrm{T}} > 24$ GeV)

Electron candidates:

- $E_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.47$

Muon candidates:

- $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$

Jet candidates:

- Built using the anti-k_t jet clustering algorithm with a radius parameter of $R = 0.4$
- $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$

Flavor tagging:

- MV1 b-tagging algorithm at 70% efficiency

All-hadronic channel

Trigger:

- At least 5 jets with $p_T > 55$ GeV

Electron candidates:

- $E_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$

Muon candidates:

- $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$

Jet candidates:

- Built using the anti-k_t jet clustering algorithm with a radius parameter of $R = 0.4$
- $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$

Flavor tagging:

- MV1 b-tagging algorithm at 57% efficiency

Function forms

Gaussian:

- $f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(x-\mu)^2}{2\sigma^2}}$

Landau:

- $f(x) = \frac{1}{\pi} \int_0^\infty e^{-t \cdot \ln t - xt} \sin(\pi t)\, dt$

Novosibirsk:

- $f(x) = Ae^{-0.5\left\{\ln^2\left(\frac{1+q_x\Lambda_\tau}{\tau^2}\right)+\tau^2\right\}}$
- $q_x = \frac{(x-x_0)}{\sigma}$
- $\Lambda_\tau = \frac{\tau \cdot \sinh\left(\tau\sqrt{\ln 4}\right)}{\tau\sqrt{\ln 4}}$