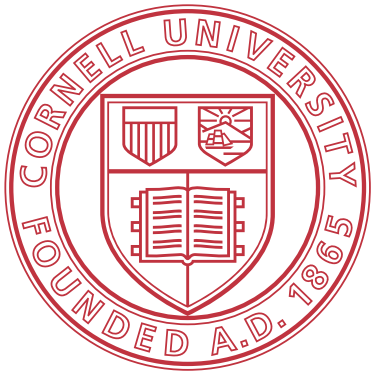
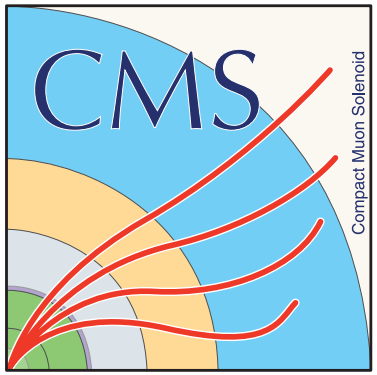
Standard Measurements of the Top Quark Mass

LHCP 2015





Nathan Mirman

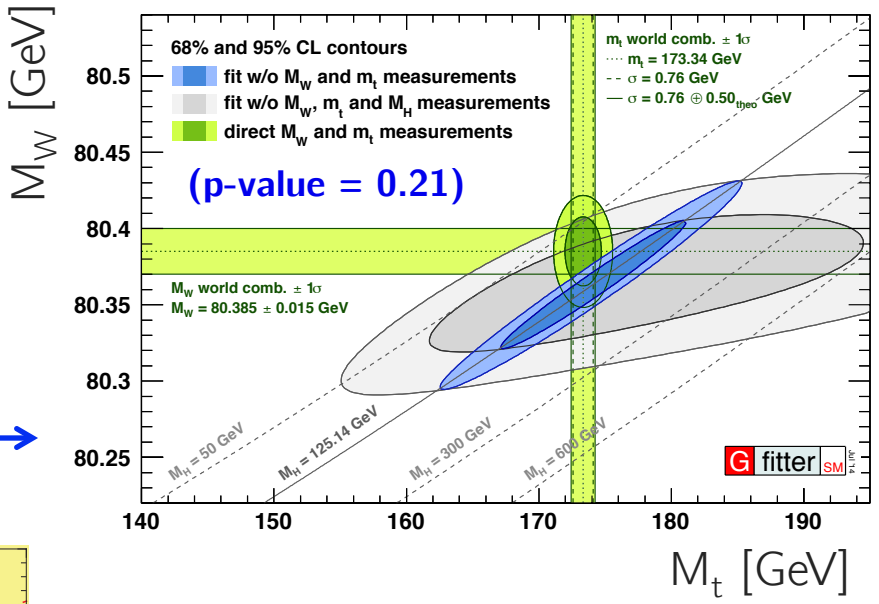
for the ATLAS and CMS collaborations

Aug 31, 2015

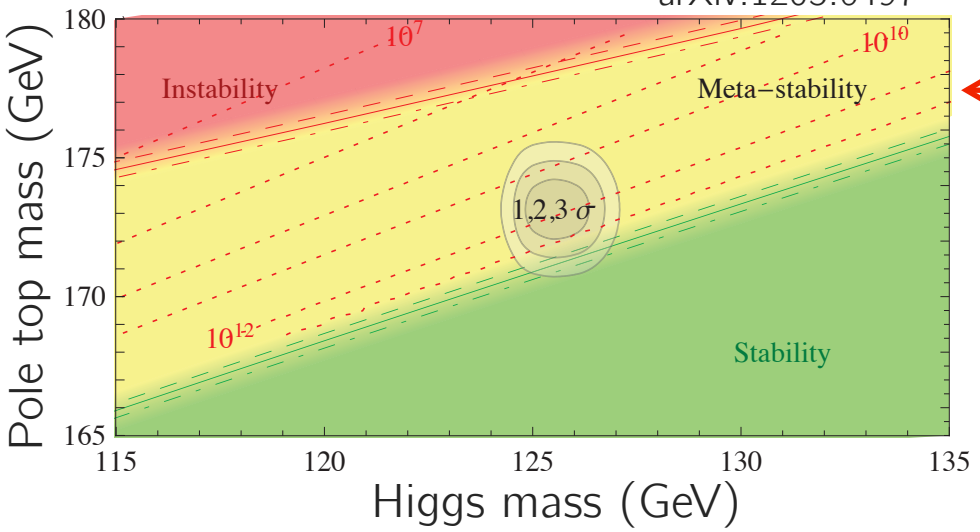
Introduction

- The top quark mass is a fundamental SM parameter.
- Decays before hadronization.
  - A colored particle which can be probed directly.
- Input into global EWK fits that test the **self-consistency of the SM**.

arXiv:1407.3792



arXiv:1205.6497



- **Stability of the EWK vacuum** at high energy scales depends on m_t.
- Here, an overview of several recent results which are calibrated to the MC to measure m_t.

Channels for m_t measurements

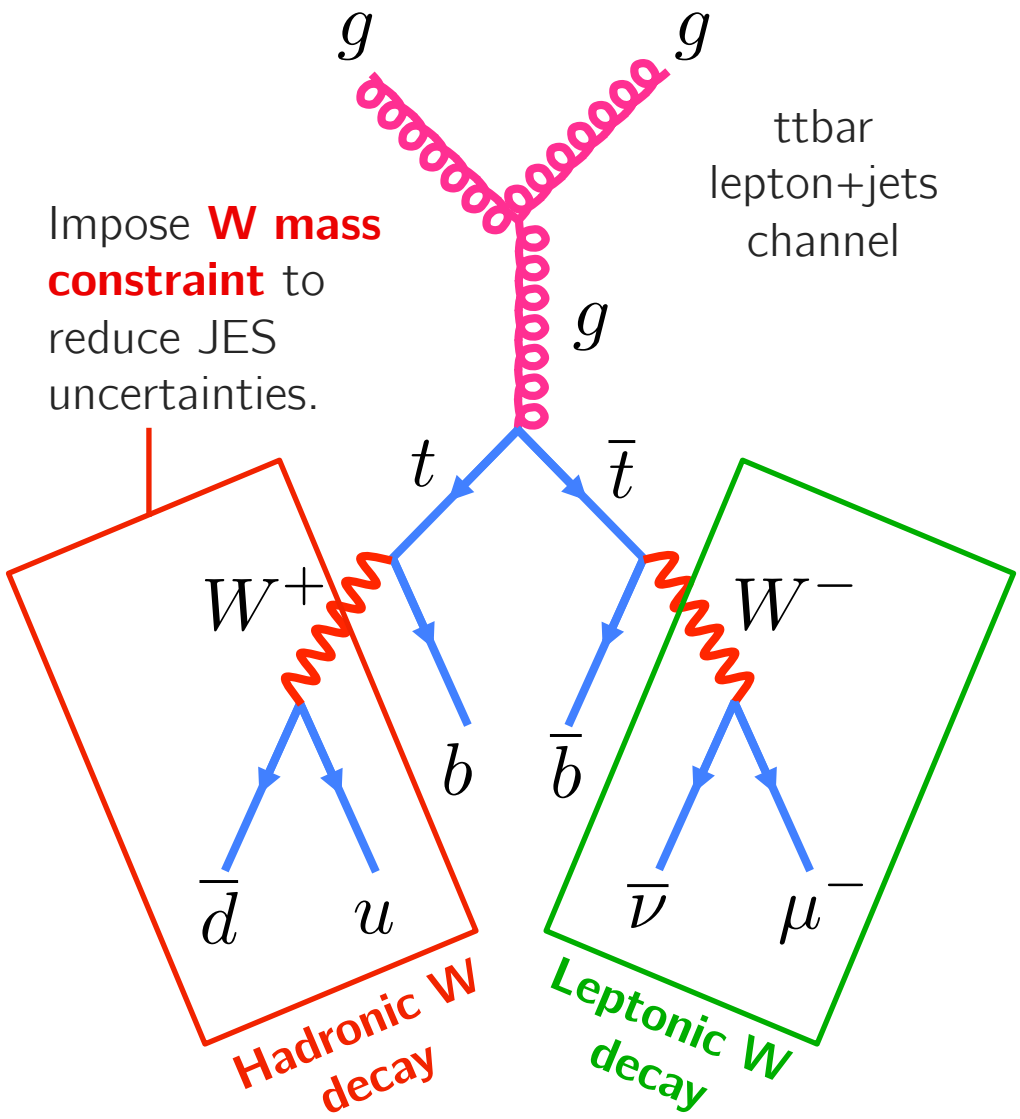
Typically, the top mass is extracted from **ttbar decays**.

- **All-hadronic** channel
  - High BR, low S/B.
- **Lepton+jets** channel
  - Most precision for m_t measurements.
- **Dilepton** channel
  - Highest S/B, underconstrained kinematics due to 2 neutrinos.

Impose **W mass constraint** to reduce JES uncertainties.

Can also utilize topologies enriched in **t-channel single top** events.

- Different regime of production and final state kinematics.



ttbar lepton+jets channel

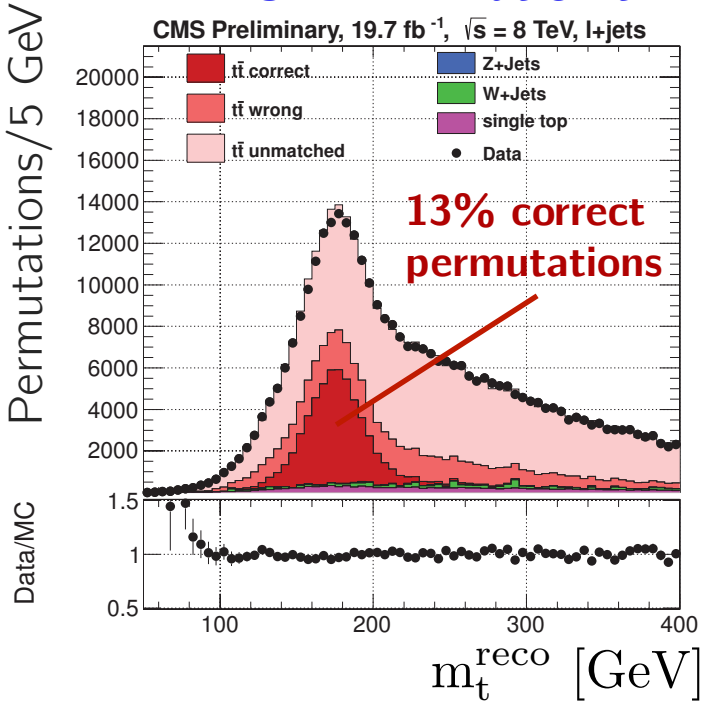
Lepton+jets: kinematic fit (CMS 8 TeV)

CMS PAS TOP-14-001

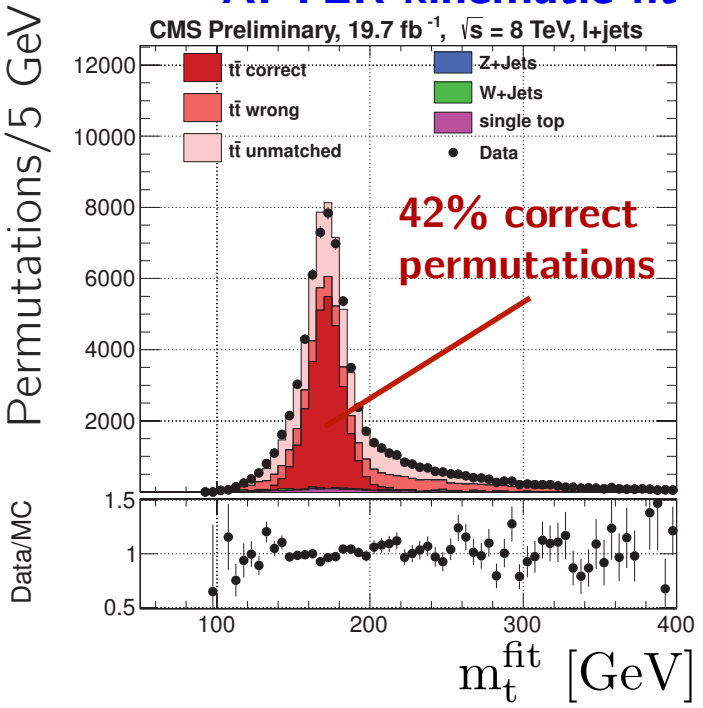
- Select a single high p_T lepton, ≥4 jets, exactly 2 b tags.
- Utilize a **kinematic fit** for event reconstruction.
  - Increases the fraction of **correct jet-parton assignments**.
  - Improves the **reconstructed m_t resolution**.
- Vary object energies within their resolutions, impose the constraints:

$$m_W = 80.4 \text{ GeV}, \; m_t = m_{tbar}.$$

BEFORE kinimatic fit

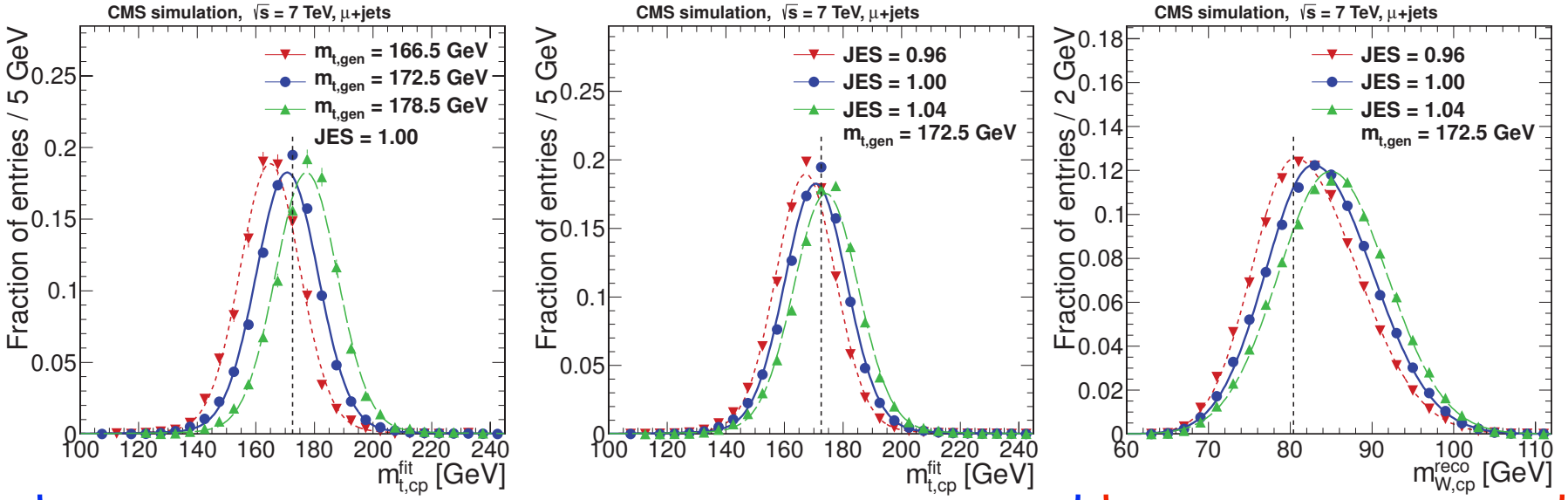


AFTER kinematic fit



Lepton+jets: 2D likelihood fit (CMS 8 TeV)

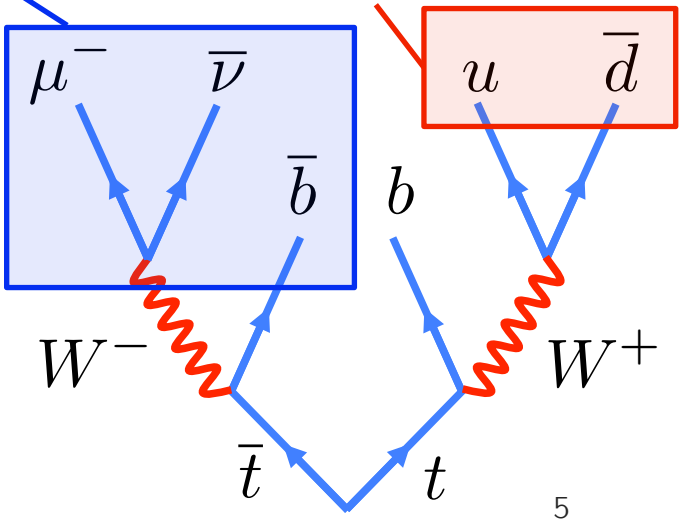
CMS PAS TOP-14-001



$P_{\mathrm{cp}}(m_t^{\mathrm{fit}}|m_t, \mathrm{JSF})$

$P_{\mathrm{cp}}(m_W^{\mathrm{reco}}|\mathrm{JSF})$

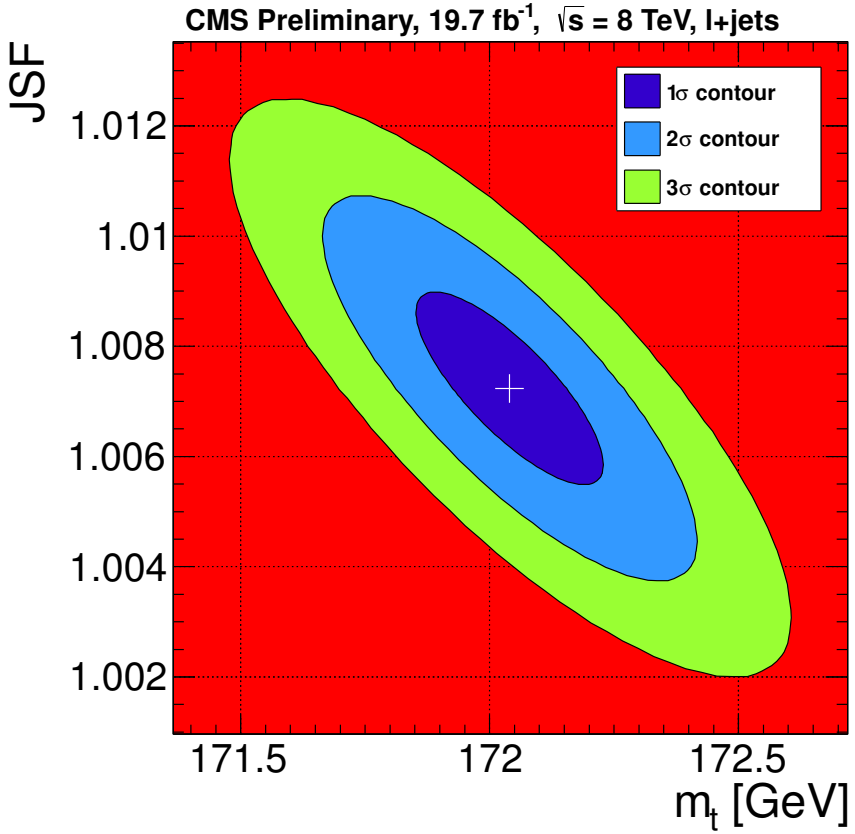
- Model the shapes of $\mathbf{m_t^{fit}}$ and $\mathbf{m_W^{reco}}$.
  - Dependence on MC top mass and Jet Scale Factor (JSF).
- The values of m_t and JSF are extracted in a 2D likelihood fit.
  - **In-situ calibration of the JES.**



Results: lepton+jets (CMS 8 TeV)

CMS PAS TOP-14-001

$\mathbf{m_t}$ = 172.04 ± 0.19 (stat+JSF) ± **0.75 (syst)** GeV
JSF = 1.007 ± 0.002 (stat) ± 0.012 (syst)



- In-situ JES calibration reduces total uncertainty from **1.29** to **0.75 GeV**.
  - **p_T and η-dependent JES uncertainty** is reduced from 1.17 to 0.18 GeV.
- Dominant systematic uncertainties:
  - **Flavor-dep. JSF:** 0.41 GeV.
  - Pile up: 0.27 GeV.
  - Jet energy resolution: 0.26 GeV.

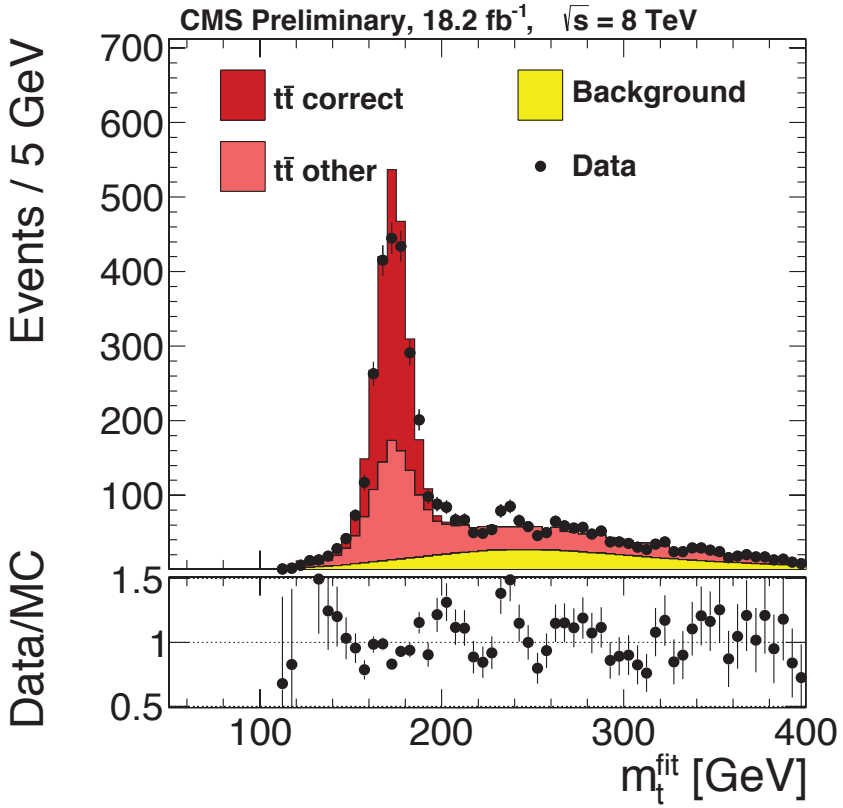
Results: all-hadronic final state (CMS 8 TeV)

CMS PAS TOP-14-002

$\mathbf{m_t}$ = 172.08 ± 0.36 (stat+JSF) ± 0.83 (syst) GeV
JSF = 1.007 ± 0.003 (stat) ± 0.011 (syst)

- Similar techniques to CMS lepton+jets result.
- Select ≥6 jets and ≥2 b tags.
- **Kinematic fit** to increase the fraction of correct ttbar permutations and improve m_t^{reco} resolution.
- **2D likelihood fit** with in-situ JES calibration.
- Dominant systematics:
  - **p_T and η-dep. JES**: 0.28 GeV
  - **Flavor-dep. JSF:** 0.36 GeV.
  - Pile up: 0.31 GeV
  - Background: 0.22 GeV

- **Multijet background** is modeled with event mixing technique.

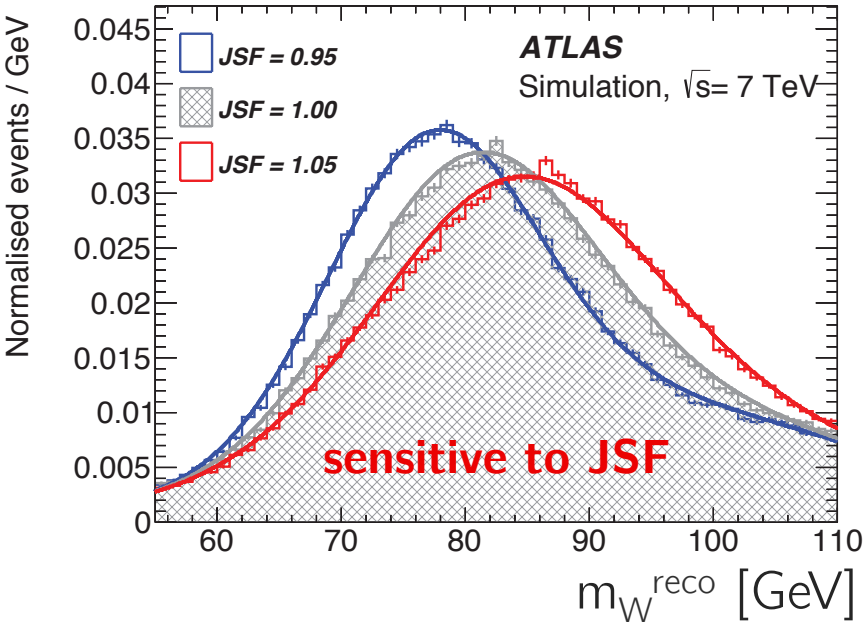


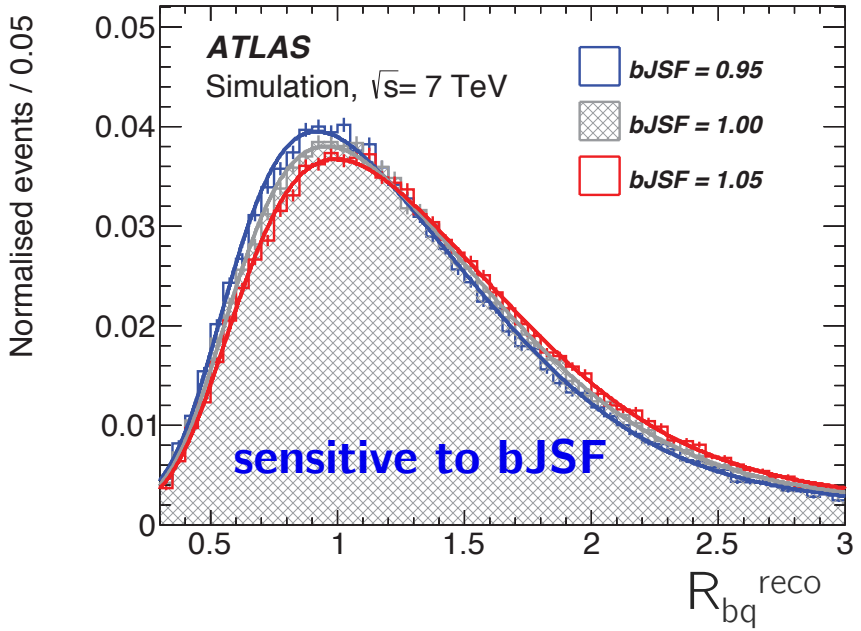
Lepton+jets: 3D likelihood fit (ATLAS 7 TeV)

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

- Select 1 high-p_T lepton, high MET, ≥4 jets, ≥1 b tag.
  - Separate fits are conducted for 1 b tag and ≥2 b tag events.
- Reconstruct ttbar system with **kinematic likelihood fit**.
  - Similar to the technique used by CMS.
- Conduct a **3D likelihood fit** with observables: $\mathbf{m_{top}^{reco}}$, $\mathbf{m_W^{reco}}$ and $\mathbf{R_{bq}}$.
  - **In-situ calibration of JES (m_W^{reco}) and bJES (R_{bq})**, relative to udsg.

$$R_{bq}^{\mathrm{reco,2b}} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{Wjet_1} + p_T^{Wjet_2}}$$





Results: lepton+jets channel (ATLAS 7 TeV)

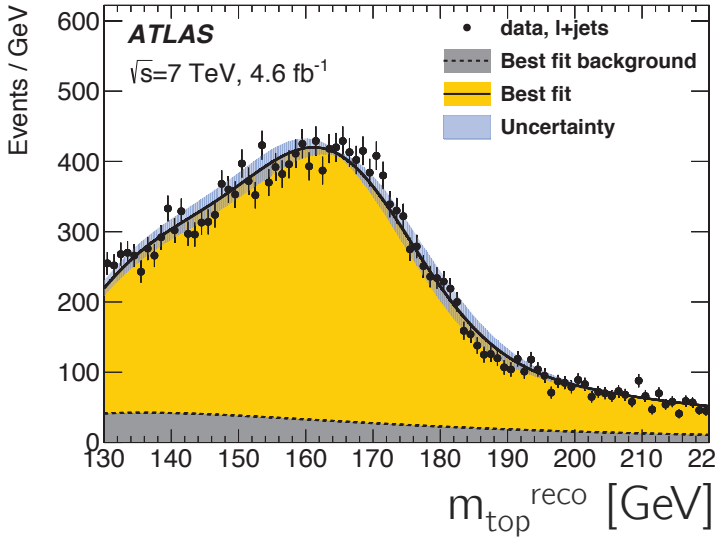
ATLAS, Eur. Phys. J. C (2015) 75:330

$\mathbf{m_t}$ = 172.33 ± 0.75 (stat+JSF+bJSF) ± **1.02 (syst)** GeV
JSF = 1.019 ± 0.003 (stat) ± 0.027 (syst)
bJSF = 1.003 ± 0.008 (stat) ± 0.023 (syst)

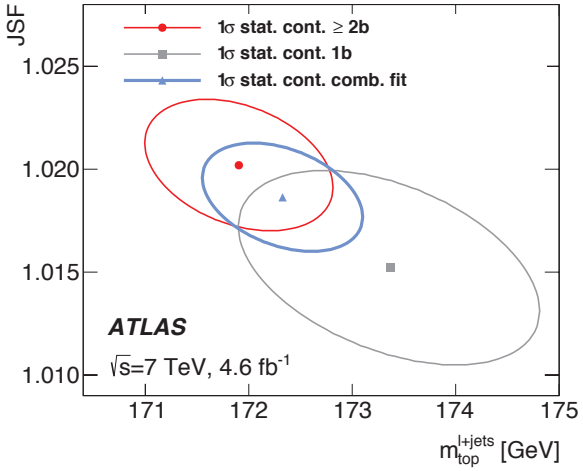
- A significant reduction of the **bJES uncertainties** is achieved by the 3D fit approach.

Major systematics:

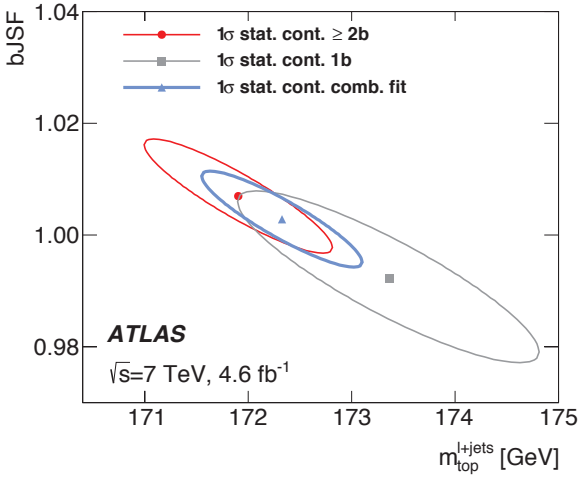
- **p_T and η-dep. JES**: 0.58 GeV.
- **bJES**: 0.06 GeV.
- b tagging: 0.50 GeV.
- ISR/FSR: 0.32 GeV.



JSF vs. m_t



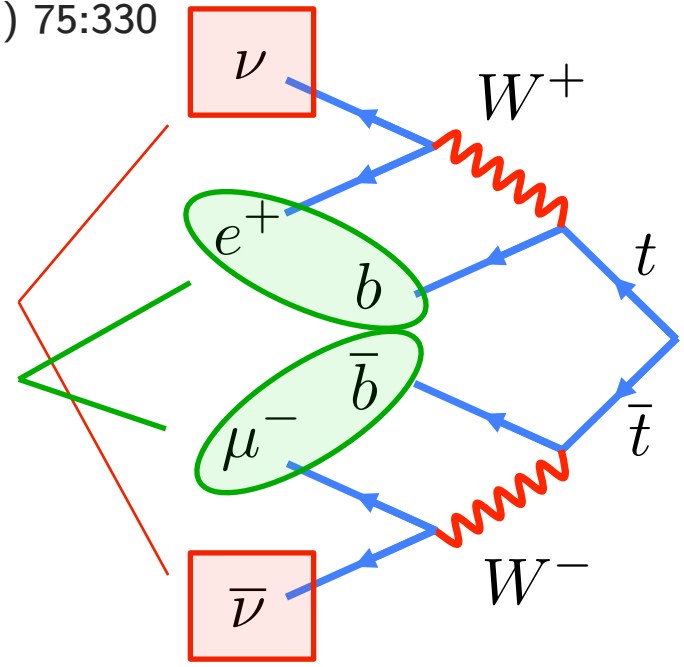
bJSF vs. m_t

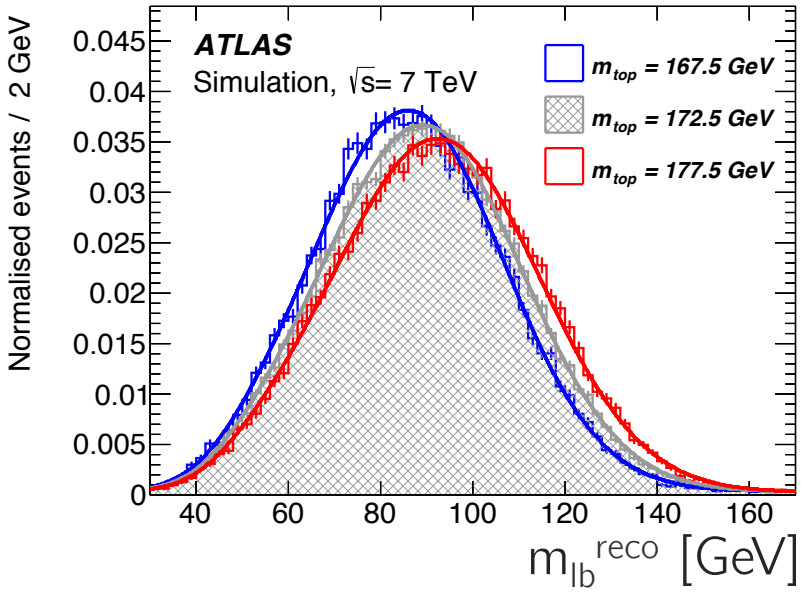


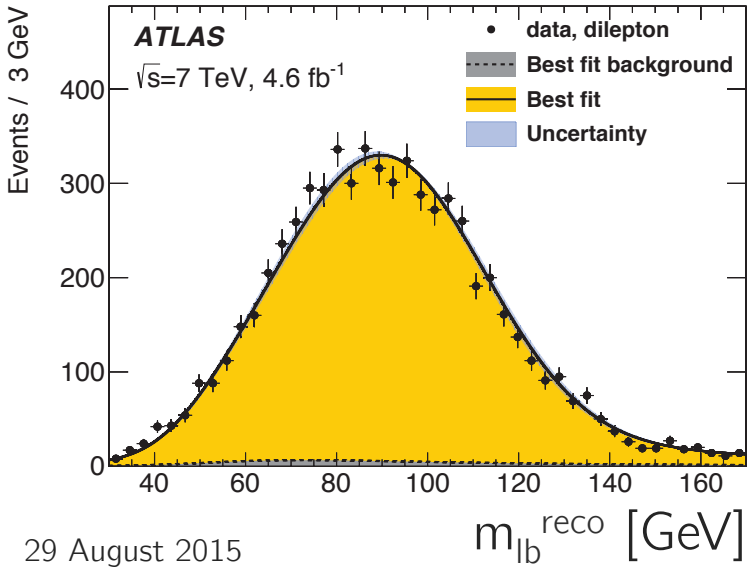
Dilepton Channel (ATLAS 7 TeV)

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

- Select 2 leptons, high MET, ≥2 jets, 1 or 2 b tags.
- **2 neutrinos → underconstrained system**
- Conduct likelihood fit with **m_{lb} observable**
  - Invariant mass between lepton, b jet pairs.
- Separate m_{lb} template shapes are obtained for signal and background.



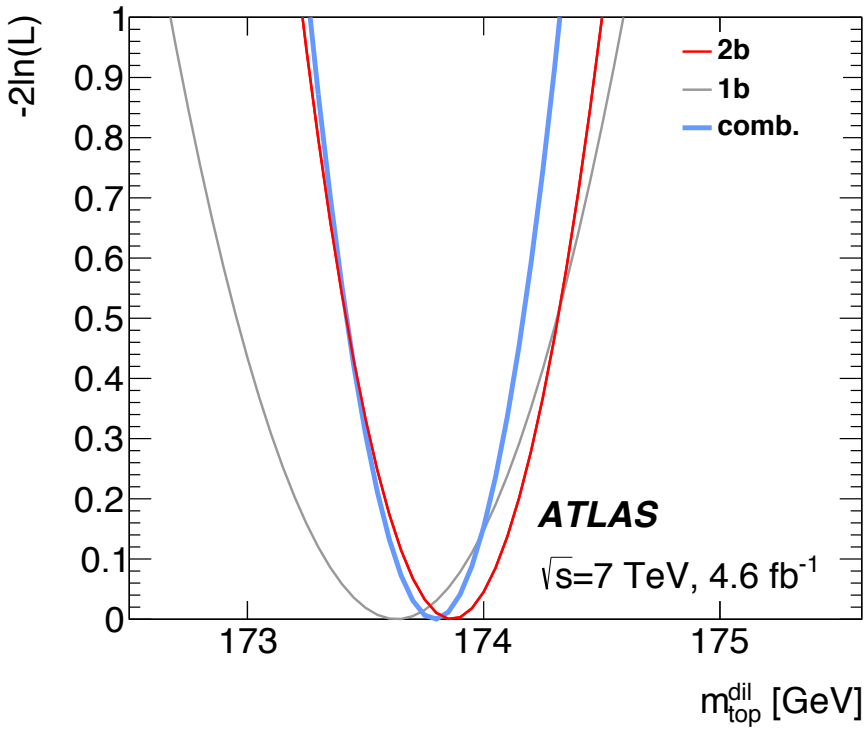




Results: dilepton channel (ATLAS 7 TeV)

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

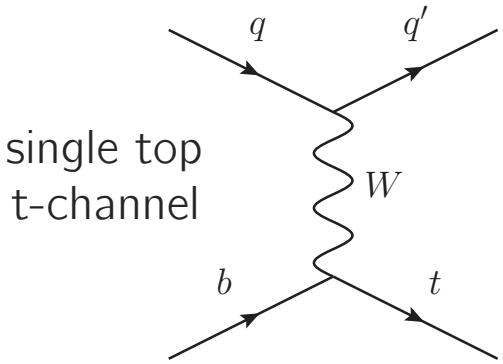
$$m_t = 173.79 \pm 0.54\ (\text{stat}) \pm 1.30\ (\text{syst})\ \text{GeV}$$



- In-situ JES calibration not implemented in the dilepton channel.
- Small sensitivity to backgrounds due to dilepton selection (0.1 GeV).
- Dominant systematics:
  - **JES:** 0.75 GeV.
  - **bJES:** 0.68 GeV.
  - Parton showering & hadronization: 0.53 GeV.
  - ISR/FSR: 0.47 GeV.

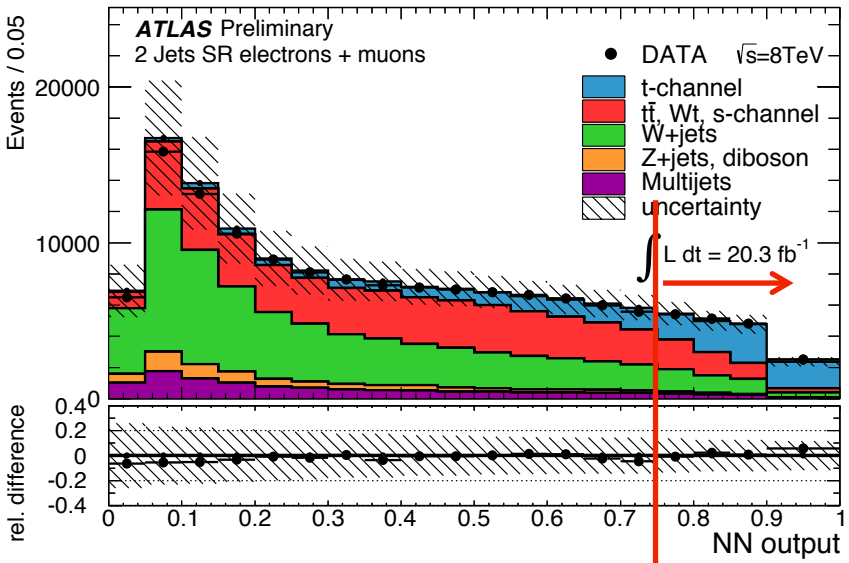
Single top enriched events (ATLAS 8 TeV)

ATLAS CONF-2014-055



- Select 1 high-p_T lepton, high MET, ≥2 jets, 1 b tag.
- Further selection is conducted using a **neural network** with 12 input variables.

- Conduct a binned likelihood fit with the **m_{lb} observable**.
  - Signal (single top + ttbar) and background shapes modeled separately.
- Single-top versus ttbar event topology:
  - Less combinatorial background.
  - Lower S/B.
  - Different color flow and production energy scale.



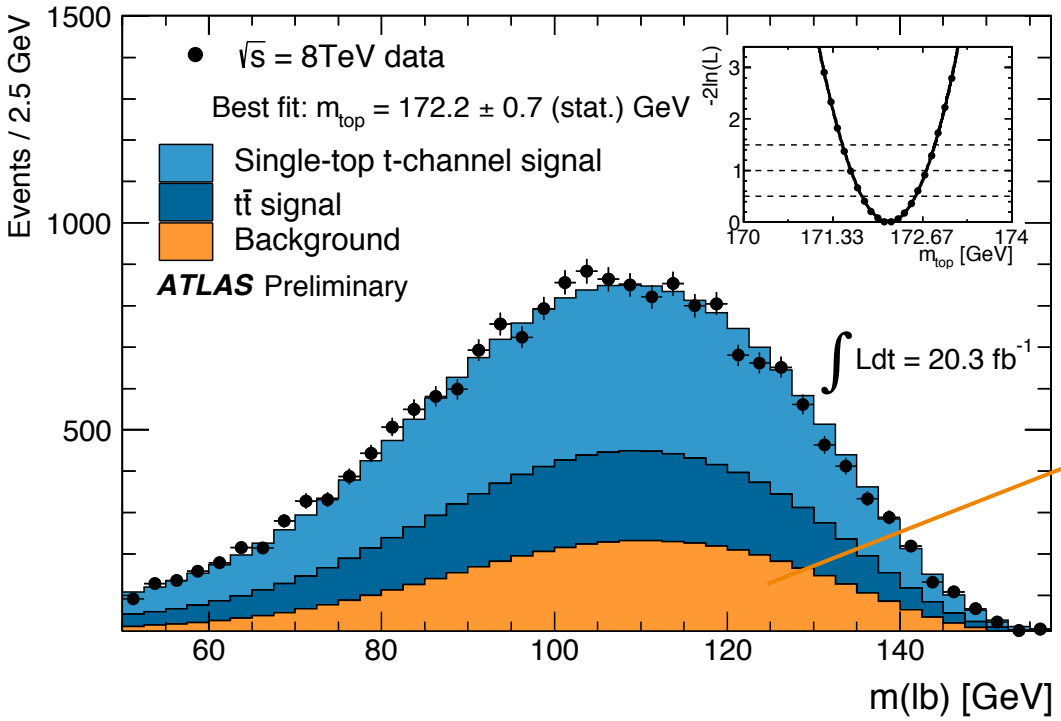
~50% t-channel events

Results: single top (ATLAS 8 TeV)

ATLAS CONF-2014-055

$$\mathbf{m_t} = 172.2 \pm 0.7\ (\text{stat}) \pm 2.0\ (\text{syst})\ \text{GeV}$$

- Results are complementary to ttbar measurements.
  - Different regime for single top production.



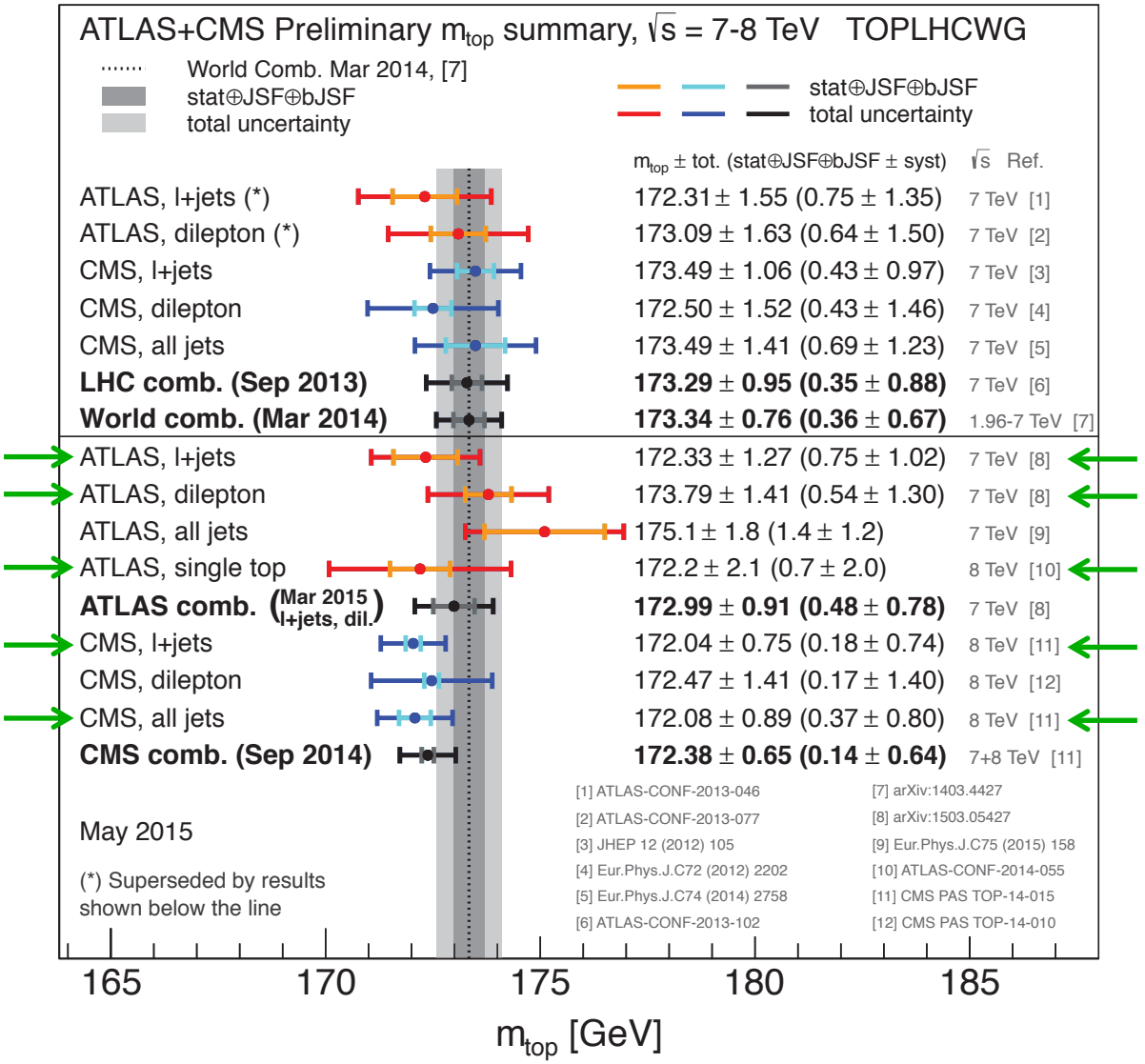
Dominant systematics:

- **JES + bJES:** 1.5 GeV.
- t-channel parton showering & hadronization: 0.7 GeV.
- **W+jets shape & normalization:** 0.5 GeV.
  - Shape component due to PDFs and flavor of jets produced in association with the W.

ATLAS and CMS Combinations

- Analyses combined using Best Linear Unbiased Estimator (BLUE) method.
  - Accounts for correlations between all uncertainties.
- Analyses reviewed today
  - So far, separate combinations by ATLAS and CMS.
- Most precise single combination uses CMS 7+8 TeV results.
  - Total uncertainty is now below 1 GeV.

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TopLHCWGSummaryPlots



Summary and Conclusions

- ATLAS and CMS have provided measurements of the top quark mass in the **ttbar all-hadronic**, **lepton+jets**, and **dilepton** channels, as well as **single top enriched events** (ATLAS only).
- In the lepton+jets and all-hadronic channels, measurements utilize techniques to **reduce their sensitivity to the JES**.
  - **2D likelihood fit** with the $\mathbf{m_t^{reco}}$ **and** $\mathbf{m_W^{reco}}$ observables (CMS lepton+jets & all-hadronic).
  - **3D likelihood fit** with the $\mathbf{m_t^{reco}}$**,** $\mathbf{m_W^{reco}}$ **and** $\mathbf{R_{bq}}$ observables (ATLAS lepton+jets).
    - Also provides sensitivity to **bJES**.
- Recent combinations by ATLAS and CMS achieve sub-GeV precision on the value of the top quark mass.

BACKUP

Additional details: lepton+jets (CMS 8 TeV)

CMS PAS TOP-14-001

2D fit w/ in-situ JES calibration

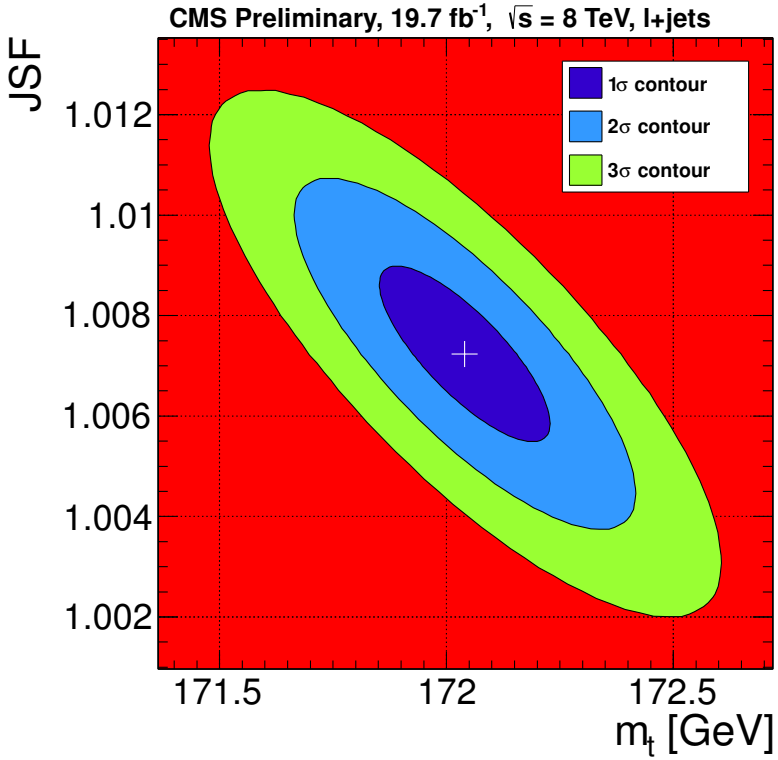
m_t = 172.04 ± 0.19 (stat+JSF) ± **0.75 (syst)** GeV

JSF = 1.007 ± 0.002 (stat) ± 0.012 (syst)

1D fit (for crosscheck)

m_t = 172.66 ± 0.11 (stat) ± **1.29 (syst)** GeV

2D fit improves p_T and η-dependent JES uncertainty from 1.17 to 0.18 GeV.



Systematic uncertainties	Δm_t^{2D} (GeV)
p_T and η-dep. JES	0.18
Pile up	0.27
Detector modeling	0.28
Method & backgrounds	0.15
Flavor dep. JSF	0.41
b frag. & decays	0.17
Signal modeling	0.39
Total	**0.75**

Additional details: all-hadronic (CMS 8 TeV)

CMS PAS TOP-14-002

2D fit w/ in-situ JES calibration

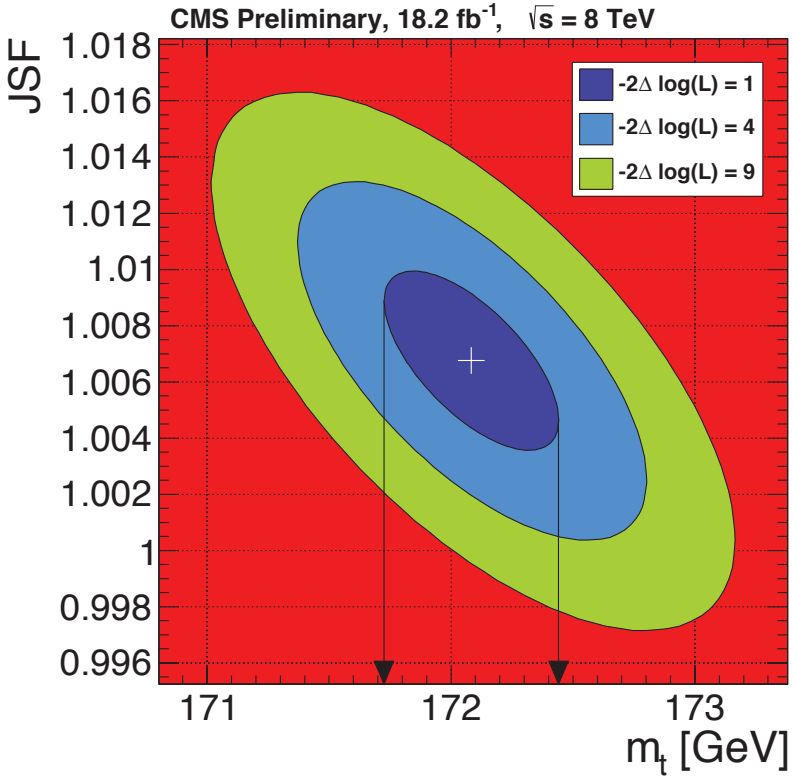
m_t = 172.08 ± 0.36 (stat+JSF) ± **0.83 (syst)** GeV

JSF = 1.007 ± 0.003 (stat) ± 0.011 (syst)

1D fit (for crosscheck)

m_t = 172.59 ± 0.27 (stat) ± **1.05 (syst)** GeV

2D fit improves p_T and η-dependent JES uncertainty from 0.86 to 0.28 GeV.



Systematic uncertainties	Δm_t^{2D} (GeV)
p_T and η-dep. JES	0.28
Pile up	0.31
Detector modeling	0.21
Method & backgrounds	0.23
Flavor dep. JSF	0.36
b frag. & decays	0.14
Signal modeling	0.45
Total	**0.83**

Additional details: lepton+jets channel (ATLAS 7 TeV)

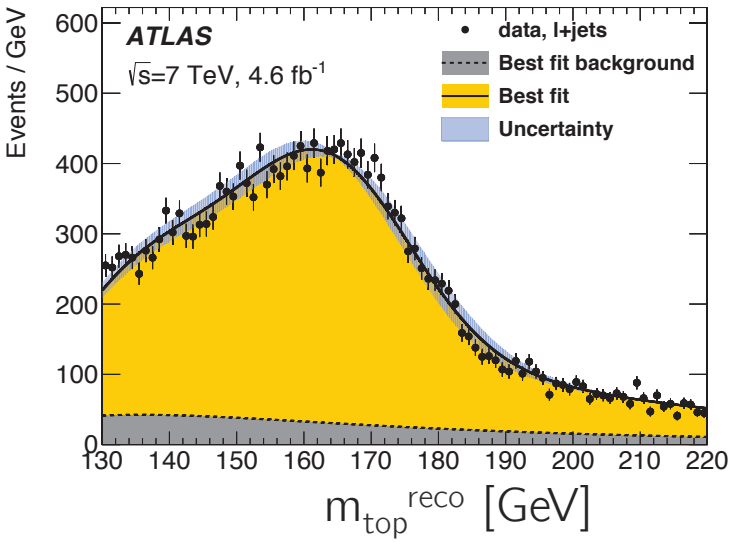
ATLAS, Eur. Phys. J. C (2015) 75:330

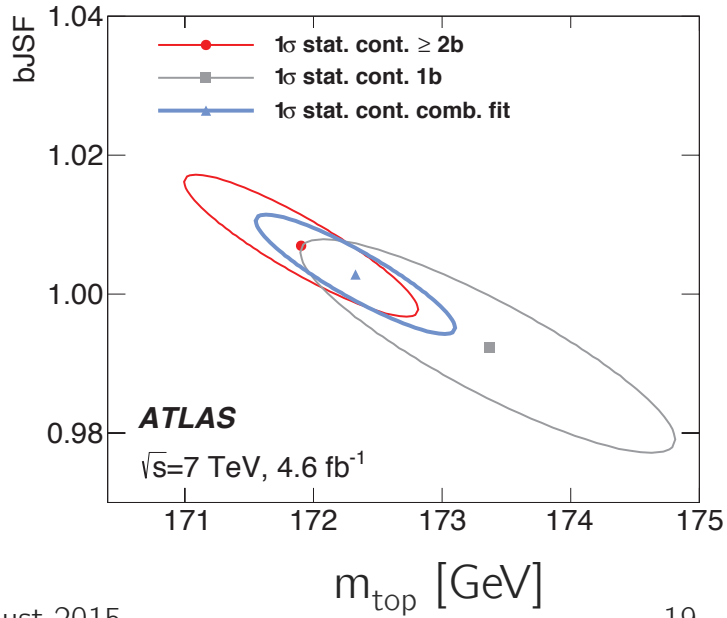
m_t = 172.33 ± 0.75 (stat+JSF+bJSF) ± 1.02 (syst) GeV
JSF = 1.019 ± 0.003 (stat) ± 0.027 (syst)
bJSF = 1.003 ± 0.008 (stat) ± 0.023 (syst)

- **bJES uncertainty** significantly reduced due to 3D fit approach.
- Dominant uncertainties are due to JES and b tagging (0.50 GeV).

Systematic uncertainties	Δm_t (GeV)
Jet energy scale	0.58
b jet energy scale	0.06
Pile up	0.02
Detector modeling	0.58
Method and backgrounds	0.33
Signal modeling	0.53
Total	**1.22**

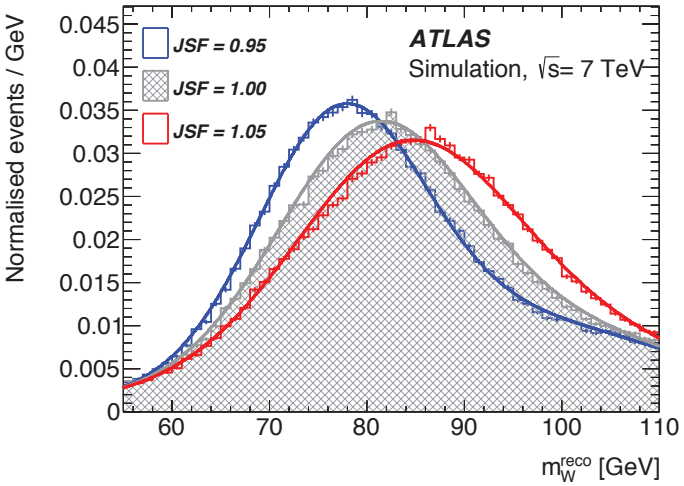
Signal + background fit to data

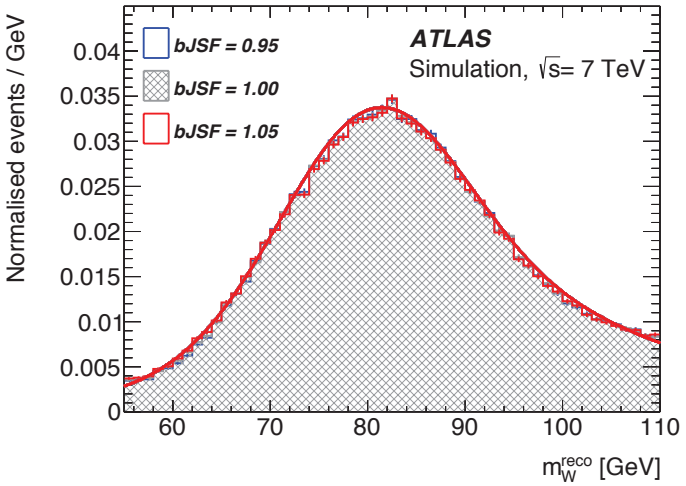


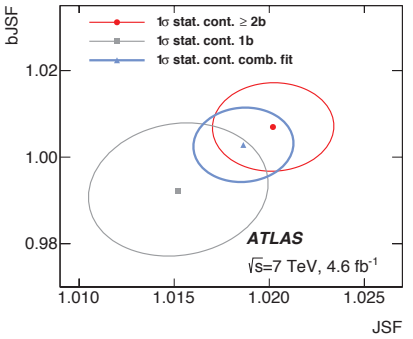


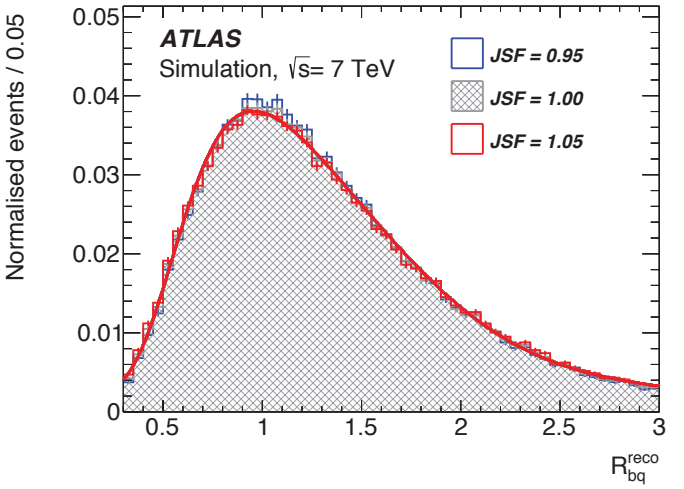
Additional details: lepton+jets channel (ATLAS 7 TeV)

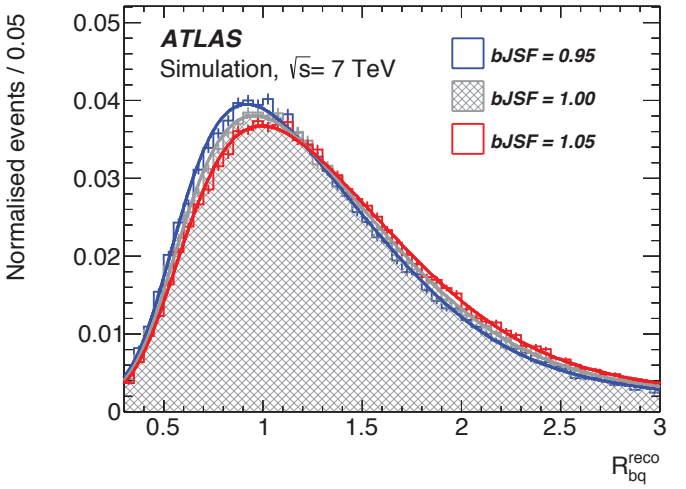
ATLAS, Eur. Phys. J. C (2015) 75:330

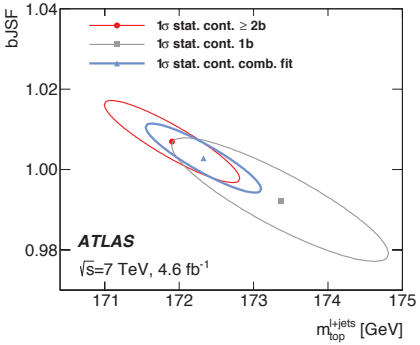


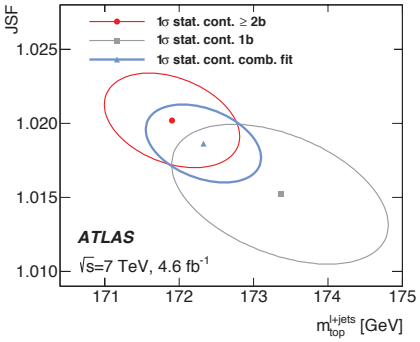










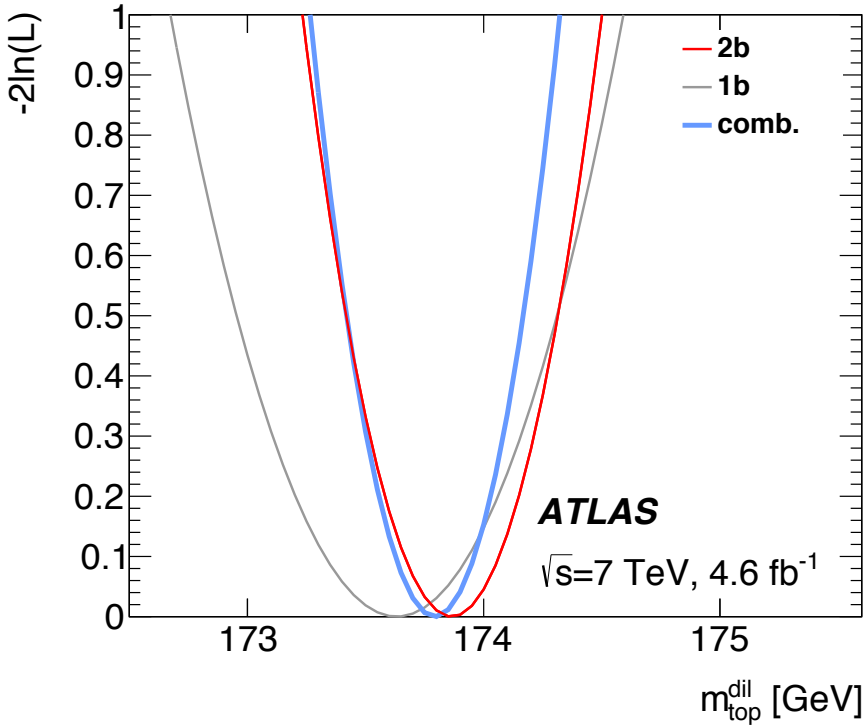


Additional details: dilepton channel (ATLAS 7 TeV)

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

$$m_t = 173.79 \pm 0.54\ (\text{stat}) \pm 1.30\ (\text{syst})\ \text{GeV}$$

- Small sensitivity to backgrounds due to very clean dilepton signal sample.
- Dominant systematics due to JES and bJES, parton showering & hadronization (0.53 GeV), and ISR/FSR (0.47 GeV).



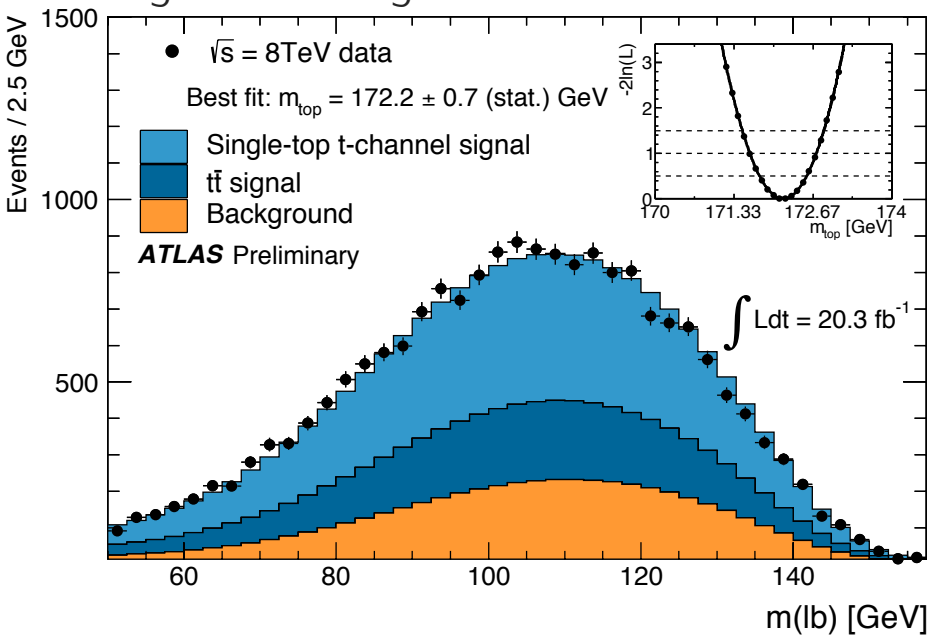
Systematic uncertainties	Δm_t (GeV)
Jet energy scale	0.75
b jet energy scale	0.68
Pile up	0.01
Detector modeling	0.25
Method and backgrounds	0.10
Signal modeling	0.78
Total	**1.30**

Additional details: single top (ATLAS 8 TeV)

ATLAS CONF-2014-055

- Dominant systematic uncertainties due to jet energy scale, W+jet background shape & normalization, and t-channel parton shower & hadronization modeling.
- Complimentary to ttbar-based measurements due to lower Q^2 regime, different backgrounds and color flow.

Signal + background fit to data



m_t = 172.2 ± 0.7 (stat) ± 2.0 (syst) GeV

Systematic uncertainties	Δm_t (GeV)
Jet energy scale & pile up	1.5
Detector modeling	0.5
W+jet background	0.5
Other backgrounds	0.5
t-channel modeling	0.8
Other top signals modeling	0.4
Total	**2.0**