Precision measurement of the top quark mass using boosted $t\bar{t}$ events with the ATLAS detector

Elliot Watton

10th April 2024
Joint APP, HEPP and NP IOP conference

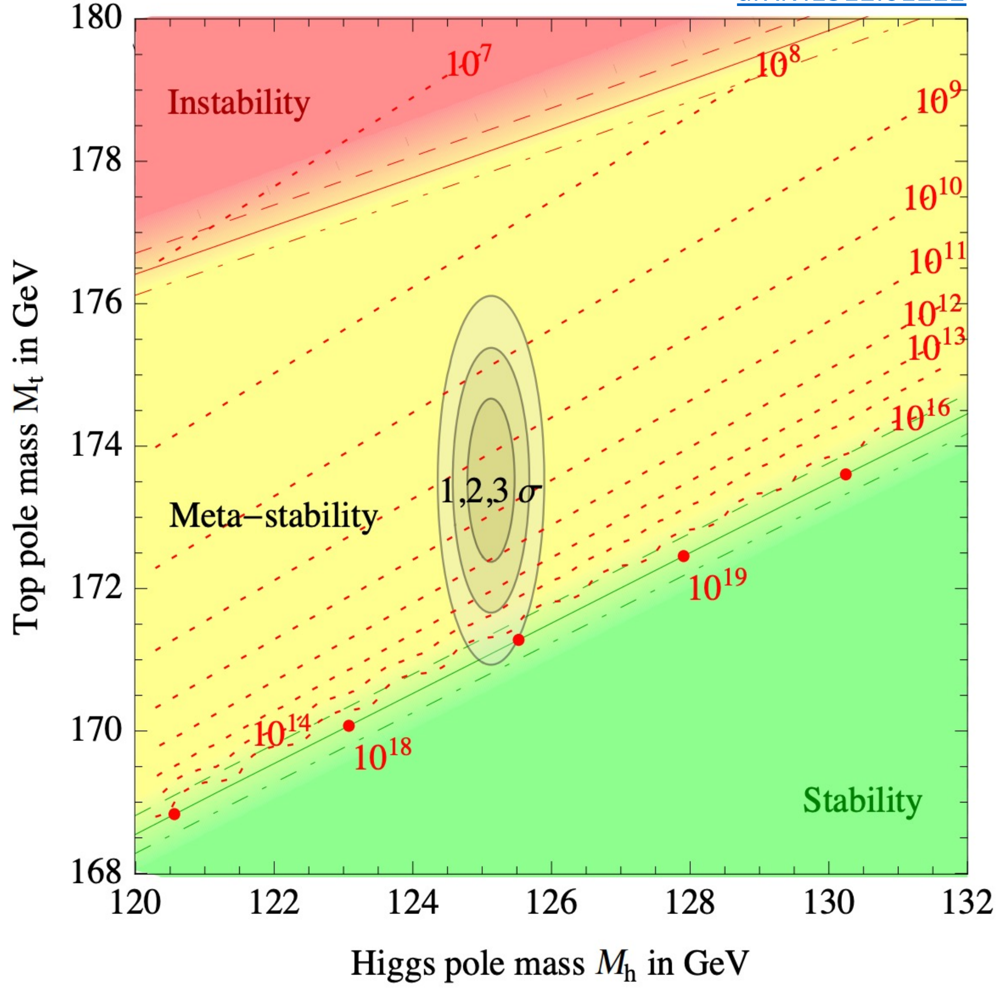
Why measure the top-quark mass?

Science and Technology Facilities Council
Rutherford Appleton Laboratory
University of Glasgow
ATLAS EXPERIMENT

- The top quark mass, m_t, is an important parameter of the Standard Model.
- m_t affects the dynamics of elementary particles via loop diagrams.
- Precision measurements of m_t provide information for global fits of electroweak parameters

  → Can assess consistency of SM and probe its extensions.

arXiv:1512.01222

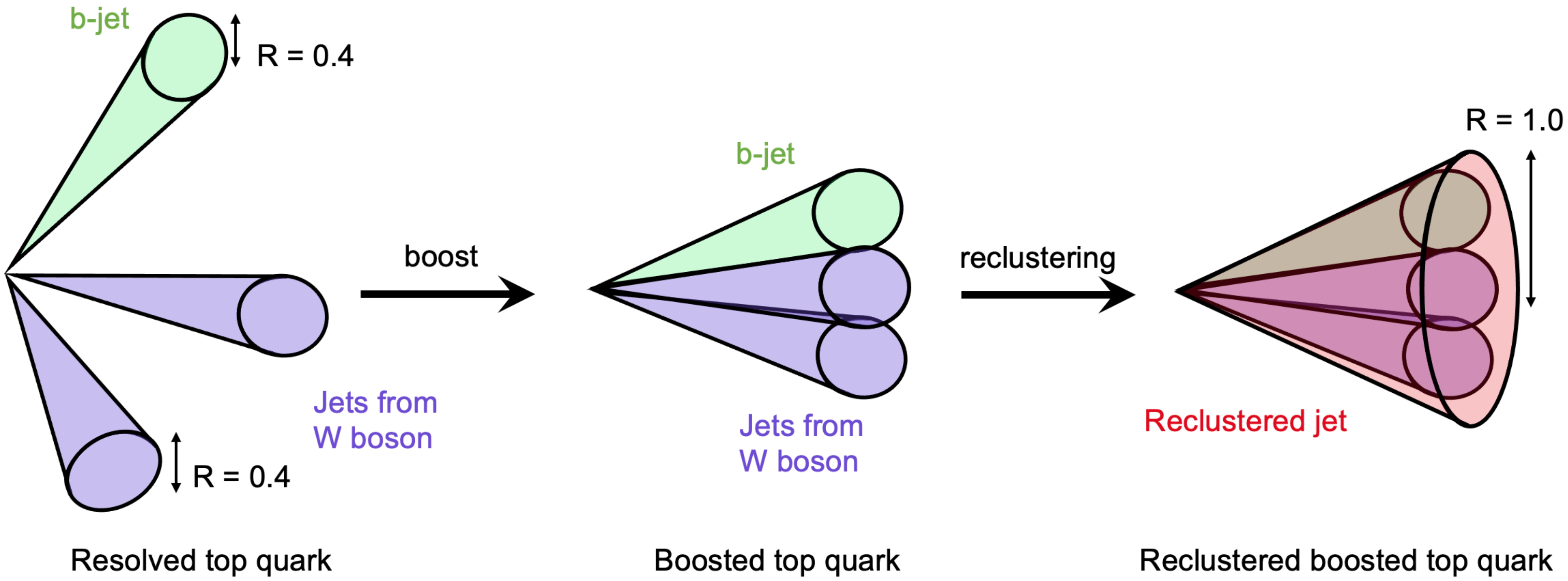


Why use boosted top quarks?

- Firstly, what is a "boosted" top quark? Consider a hadronically decaying top quark, $t \rightarrow Wb \rightarrow q\bar{q}'b$, where we have three jets:

Let's say that a top quark is boosted if:

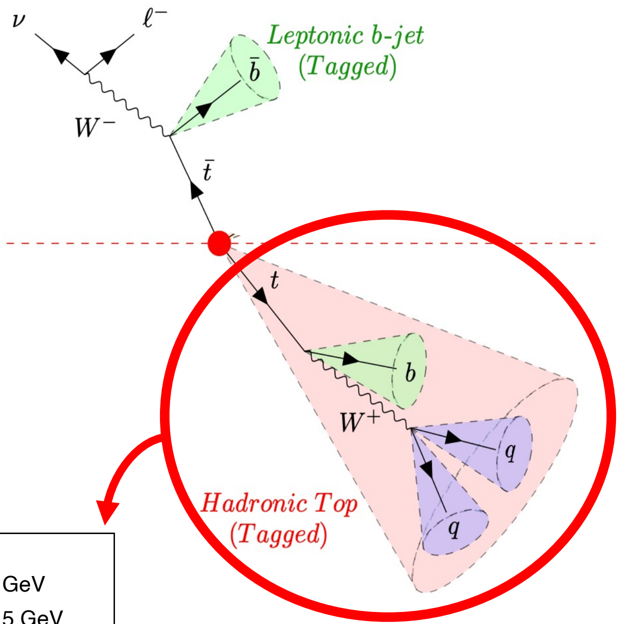
$p_T > 2m_t$

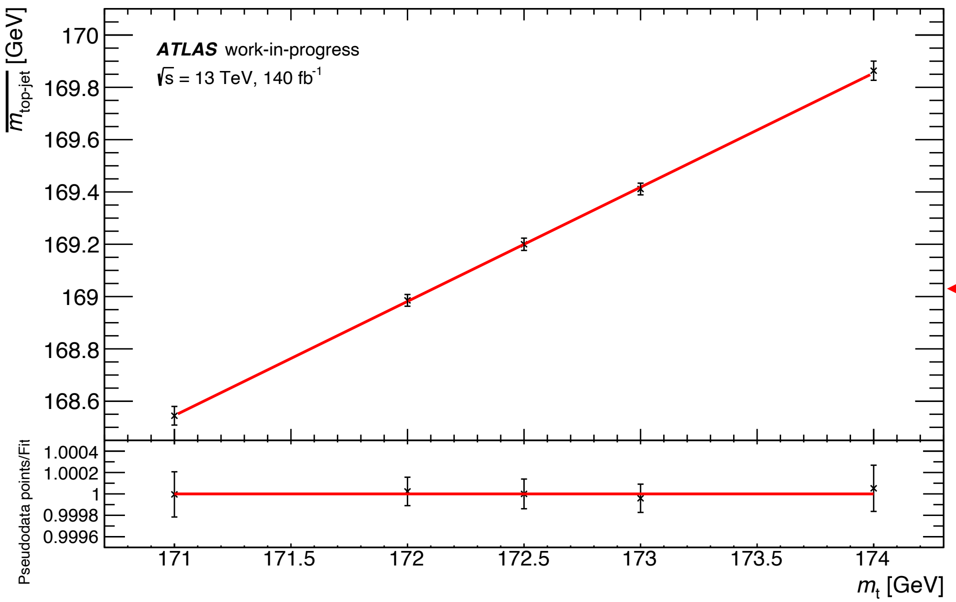


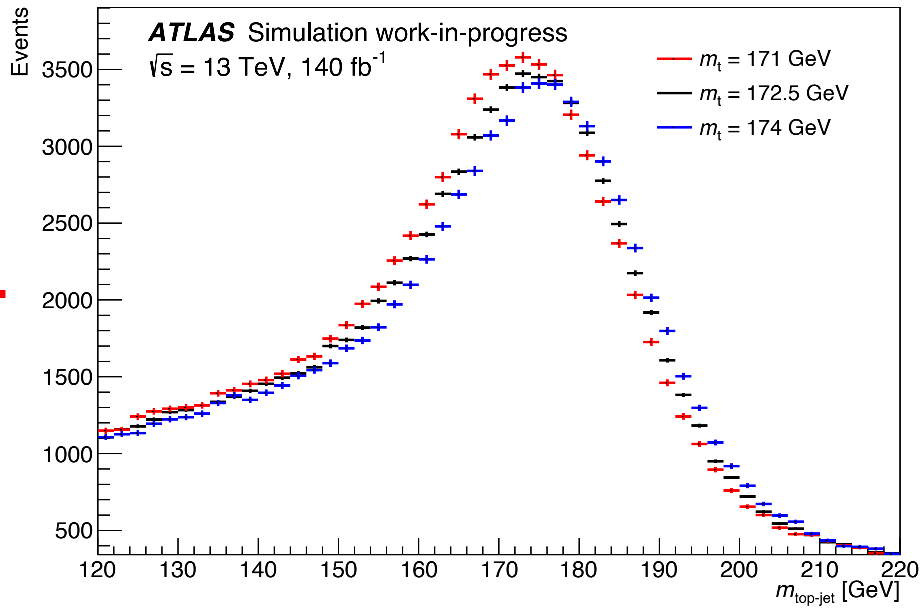
- Why use these boosted top quarks?
  - Less ambiguity in assigning jets than in the resolved (not boosted) case.
  - Increasingly higher energies at the LHC lead to more boosted top quarks relative to resolved top quarks.

Analysis strategy

- Measure m_t using kinematic reconstruction of decay products.
- Looking at the lepton+jets channel, where events have at least one large-R reclustered top-jet with:
  - $p_T > 355$ GeV
  - 120 GeV < $m_{top-jet}$ < 220 GeV
  - At least two sub-jets, at least one of which must be b-tagged.
- Use the mean of the top-jet's mass distribution, $\overline{m_{top-jet}}$, as the m_t sensitive variable.

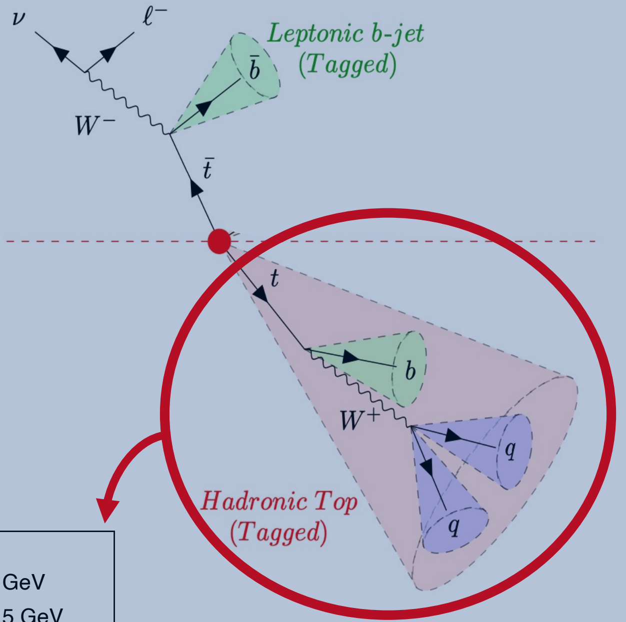






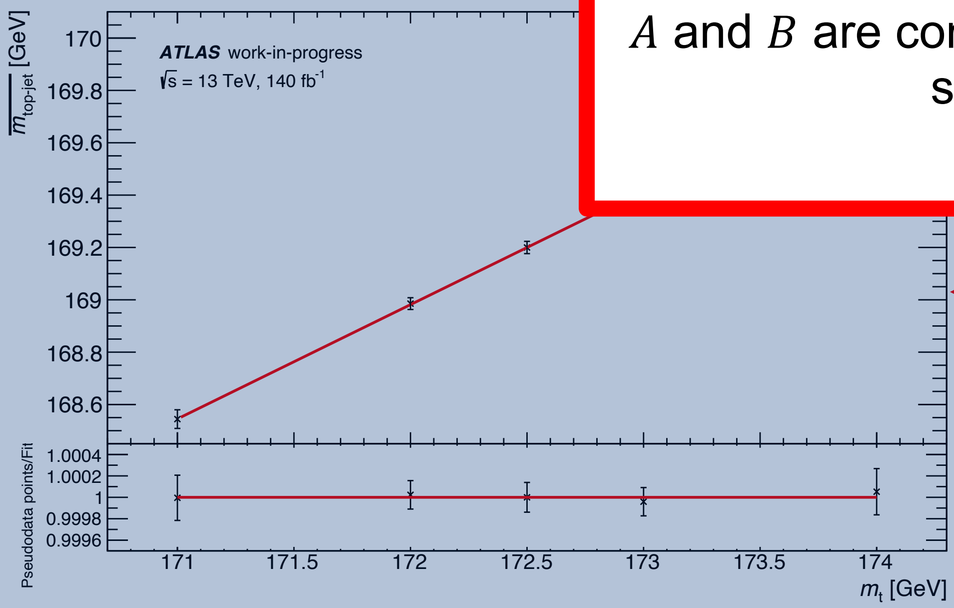
Analysis strategy

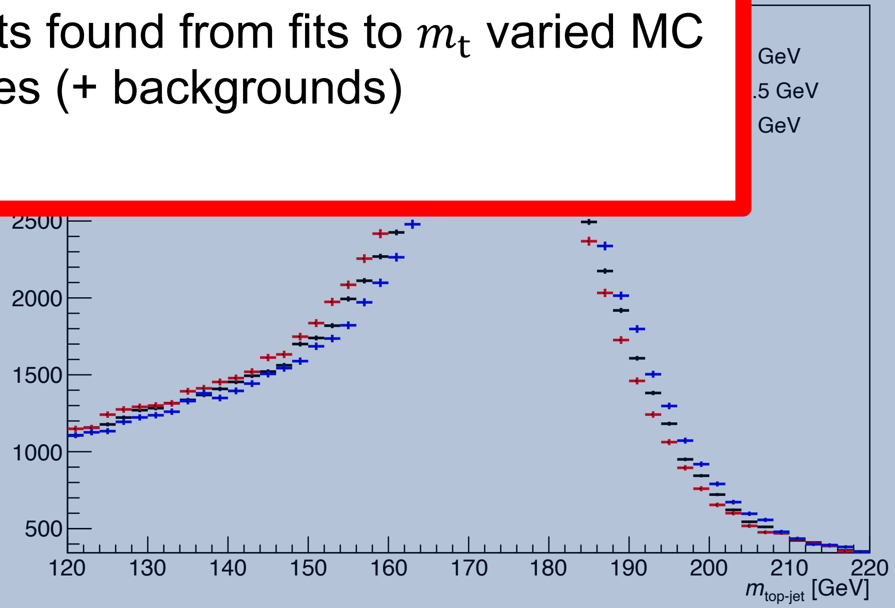
- Measure m_t using kinematic reconstruction of decay products.
- Looking at the lepton+jets channel, where events have at least one large-R reclustered top-jet with:
  - $p_T > 355$ GeV
  - 120 GeV < $m_{top-jet}$ < 22
  - At least two sub-jets, at le
- Use the mean of the top-jet's r



$$\overline{m_{top-jet}}(m_t) = A + B(m_t - 172.5)$$

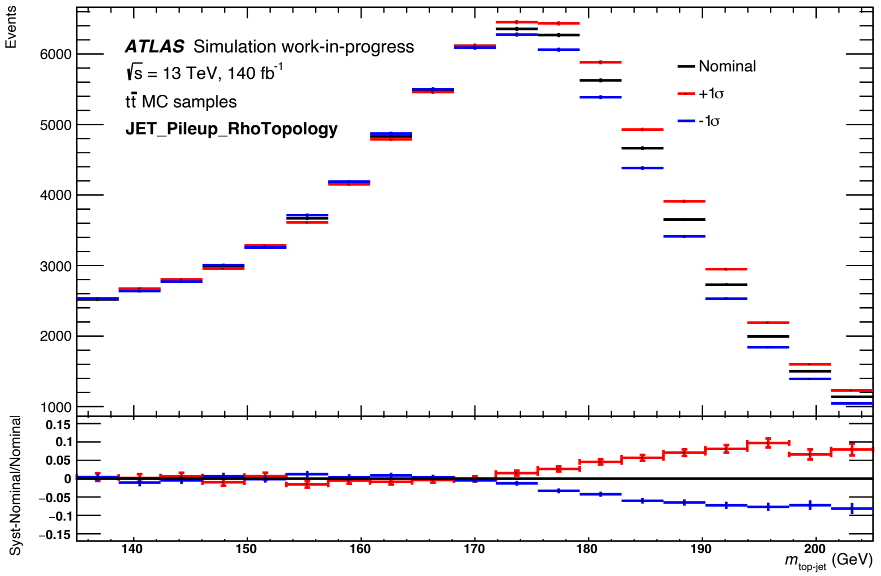
A and B are constants found from fits to m_t varied MC samples (+ backgrounds)

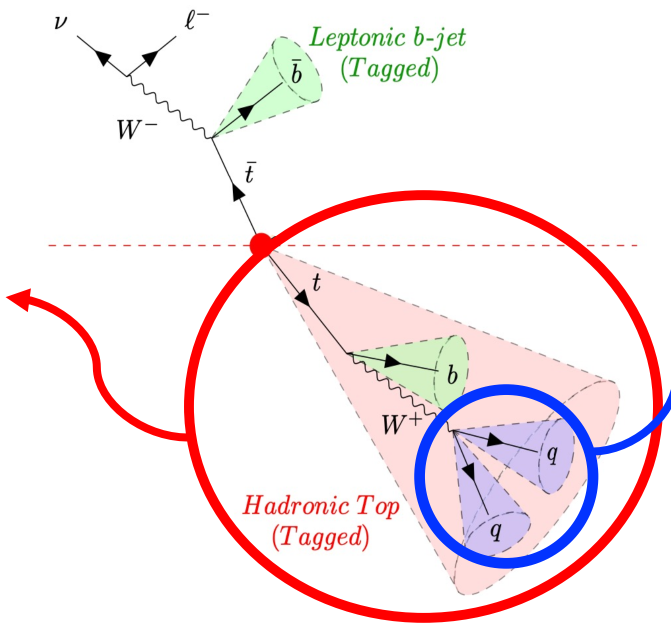


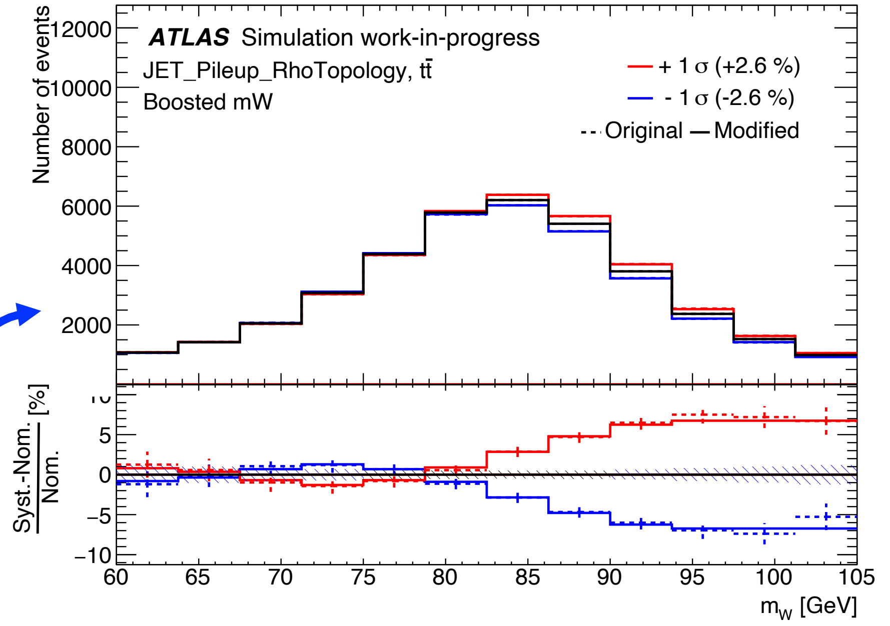


Can we reduce the impact of our uncertainties?

- For a **precision** measurement, we need a way to reduce the impact the systematic uncertainties!
- Reconstruct the W boson mass distribution, m_{W}, inside the top-jet to reduce the impact of jet energy scale (JES) uncertainties. This variable is **independent** of m_{t}.
- Use the two light-quark jet constituents with the highest p_{T} inside the top-jet.
- Idea is to use a **profile likelihood fit** to extract m_{t}, where uncertainties enter as nuisance parameters (NP)
  → 1 systematic uncertainty = 1 NP

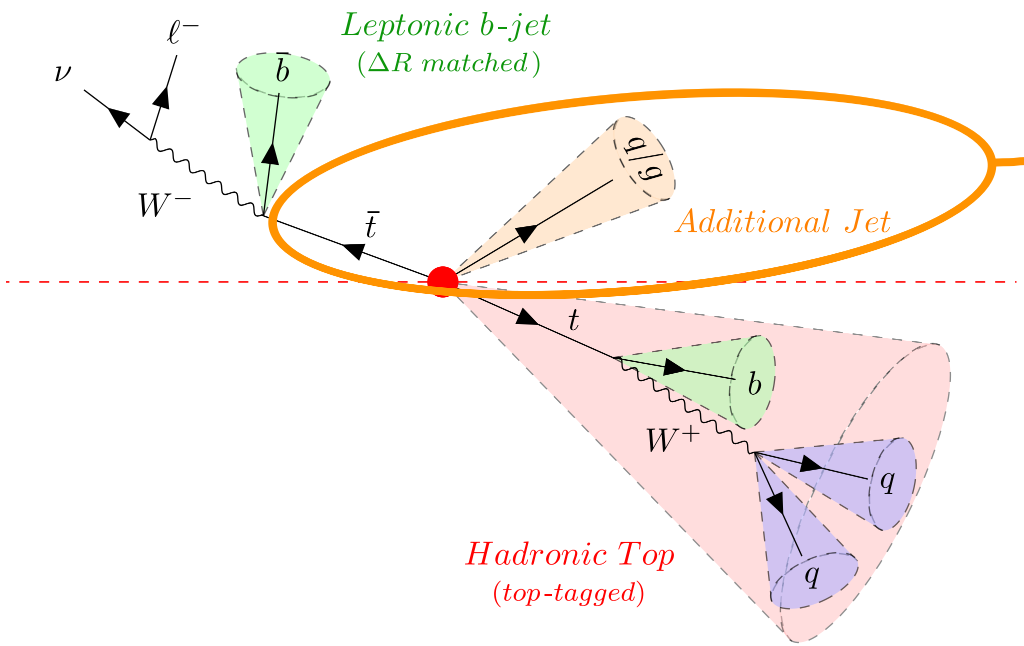


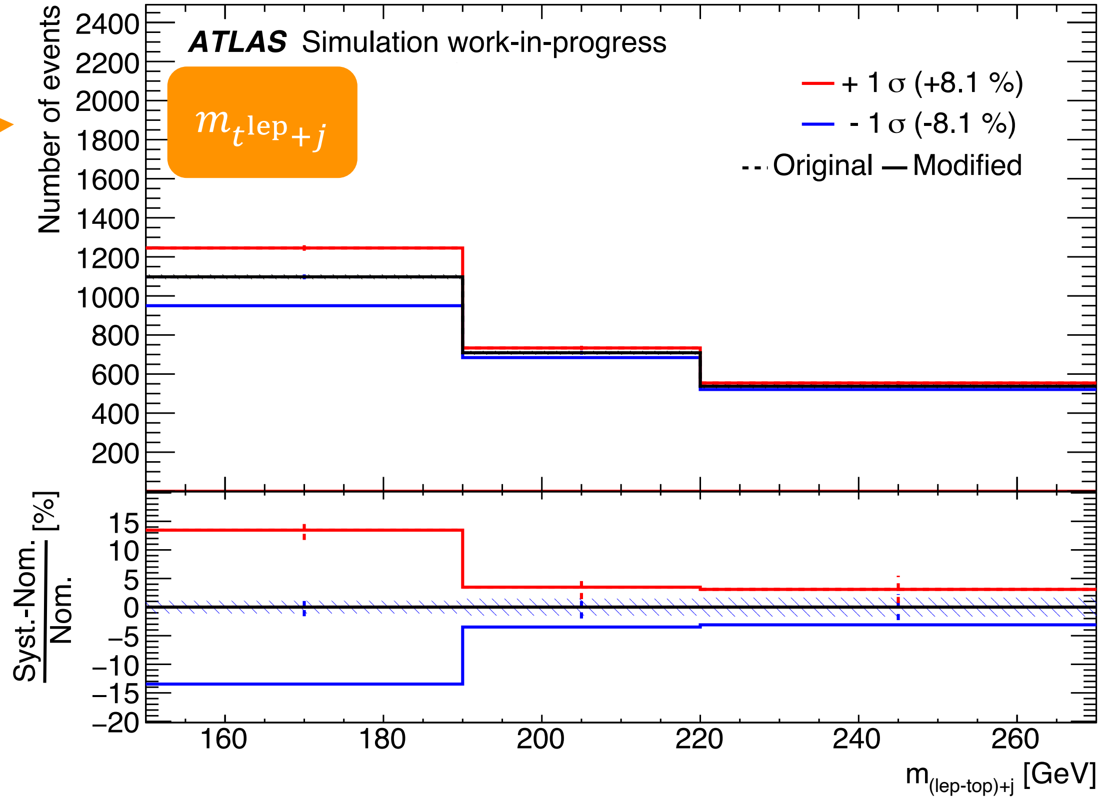




Another observable

- When simulating signal $t\bar{t}$ events, a model must be chosen for how gluons radiate during the decay.
- There are two "best" choices for the model. These impact the radiation from the b-quark in the decay in different ways leading to potentially different m_{t} results → an uncertainty is associated to the choice of model.
- Chose to reconstruct the invariant mass of the leptonically-decaying top and the closest additional jet, $m_{t^{\mathrm{lep}}+\mathrm{j}}$, to constrain this uncertainty.





Profile-likelihood fitting approach

- Construct the full likelihood as the product of likelihoods for each observable, where:
  - The top mass sensitivity comes from the $m_{\mathrm{top-jet}}$ distribution,
  - Systematic constraints enter from the m_{W} and $m_{t_{\mathrm{lep}}+\mathrm{j}}$ distributions.

$$L\left(\overline{m_{\mathrm{top-jet}}}^{\mathrm{data}}, n^{\mathrm{data}}_{m_{\mathrm{W}},\mathrm{j}}, n^{\mathrm{data}}_{m_{t_{\mathrm{lep}}+\mathrm{j}},k} \middle| m_{\mathrm{t}}, \mu_{t\bar{t}}, \underline{\theta}\right) = G\left[\overline{m_{\mathrm{top-jet}}}^{\mathrm{data}} \middle| \overline{m_{\mathrm{top-jet}}}(m_{\mathrm{t}}, \underline{\theta}), \sigma_{\overline{m_{\mathrm{top-jet}}}}\right]$$
$$\times \prod_j \mathrm{P}\left(\mathrm{n}^{\mathrm{data}}_{m_{\mathrm{W}},j} \middle| \nu_j(\mu_{t\bar{t}}, \underline{\theta})\right)$$
$$\times \prod_k \mathrm{P}\left(\mathrm{n}^{\mathrm{data}}_{m_{t_{\mathrm{lep}}+\mathrm{j}},k} \middle| \rho_{\mathrm{k}}(\mu_{t\bar{t}}, \underline{\theta})\right)$$
$$\times \prod_i G(\alpha_i | \theta_i, 1)$$

Precision?

ATLAS work-in-progress

Source	Uncertainty (GeV)	
	$\overline{m_{\text{top-jet}}}$ only fit	Full fit
JES	± 1.49	± 0.43
Radiation (ISR and FSR)	± 0.87	± 0.22
Recoil	± 0.17	± 0.10

This is just a **sub-set** of the uncertainties included in the analysis

~3x reduction

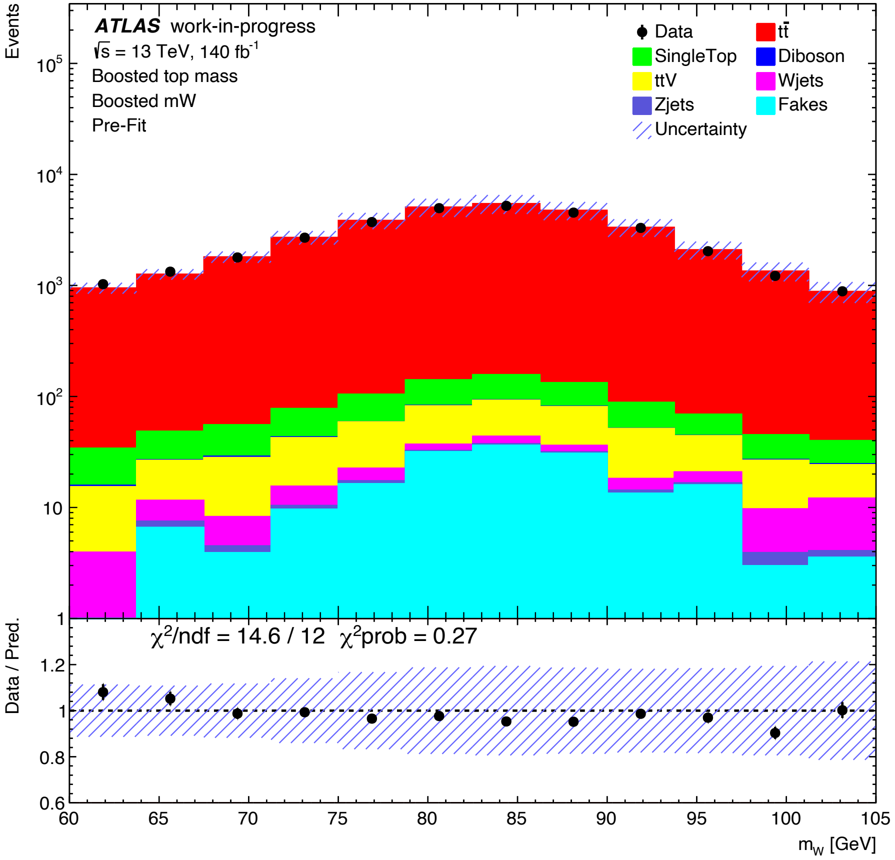
~4x reduction

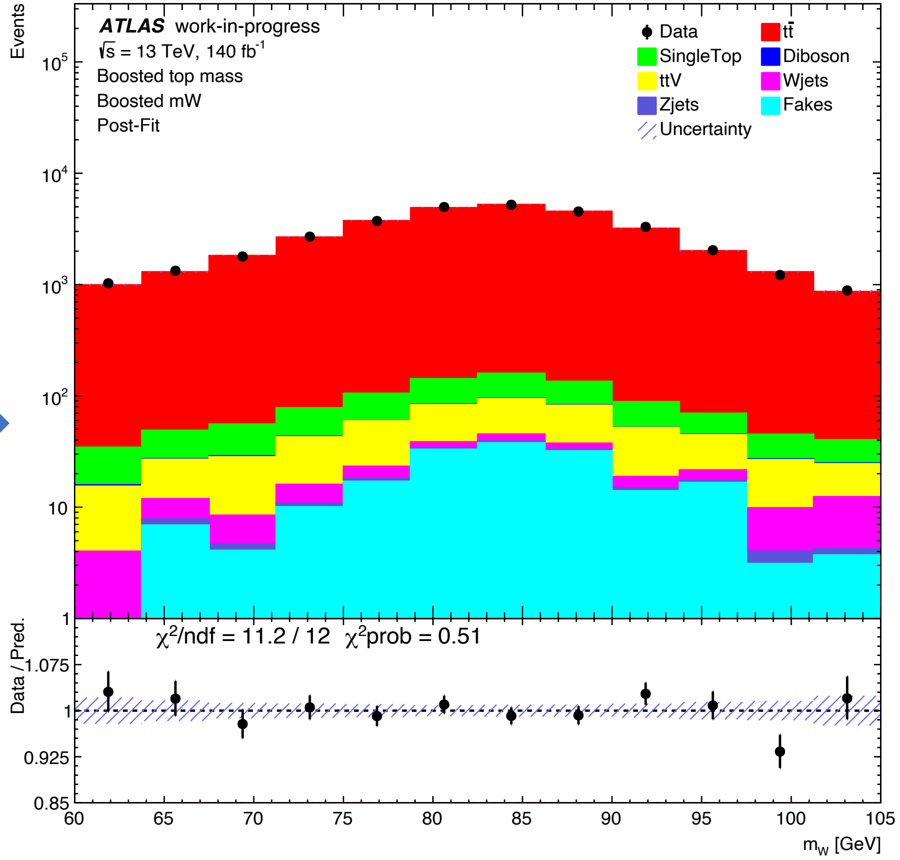
Would be $\pm$ 0.54 GeV without including $m_{t^{\text{lep}}+\text{j}}$

- Great reduction in uncertainty impacts by including m_{W} and $m_{t^{\text{lep}}+\text{j}}$ into the fit!
- Precision on m_{t} of < 1 GeV achieveable!

First look at the data

- Start by fitting only m_W distribution. **Fit is blind to m_t.**





- See that the data is well modelled!
- Some shape difference between data & MC seen pre-fit, but within uncertainties.
- The fit can adjust the model to better fit the data!

Summary

- Analysis goal is to perform a precise measurement of m_{t} using boosted $t\bar{t}$ events.

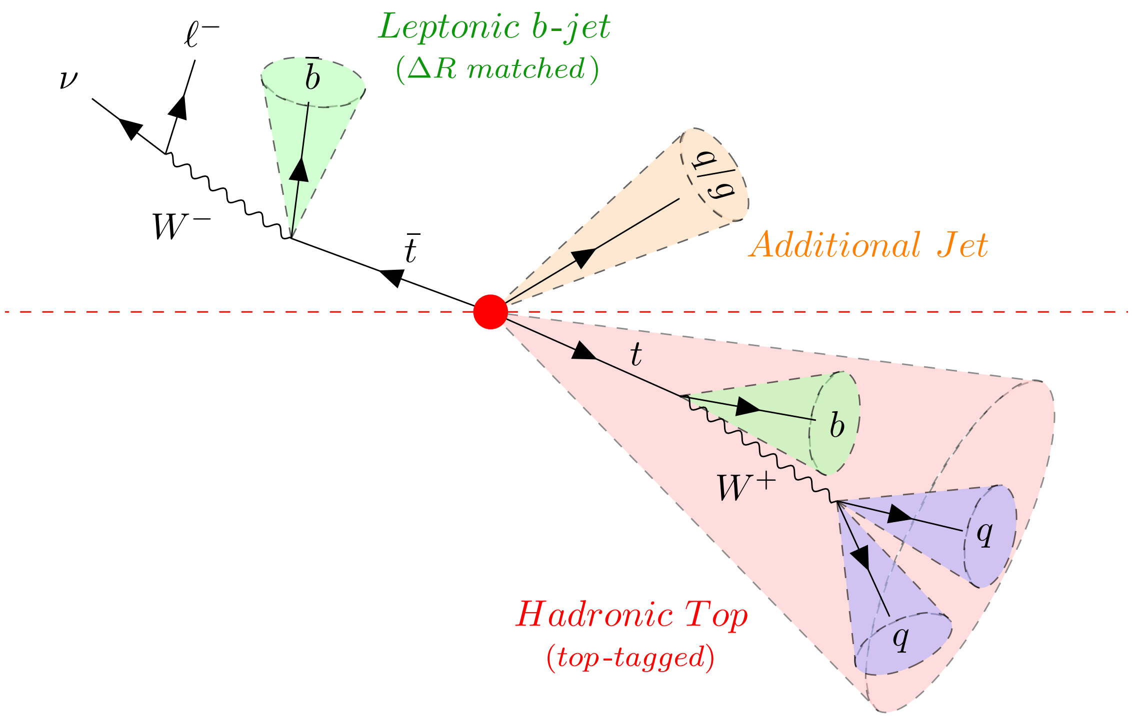
- Used a profile-likelihood fit to extract m_{t} where:
  - $\overline{m_{\mathrm{top-jet}}}$ is the m_{t} sensitive variable.
  - m_{W} and $m_{t^{\mathrm{lep}}+j}$ distributions used to reduce the impacts of the systematics.
  - Great expected precision and good data-MC agreement!

- Still need to perform some more fit studies before unblinding.

- Thank you for listening!

Backup

Selection criteria (before observable selections)



Object	Detector-level requirements		Particle-level requirements
Leptons	**Exactly 1 lepton in event**		**Exactly 1 lepton in event**
	Electrons	Muons	
	$p_T > 27$ GeV	$p_T > 27$ GeV	$p_T > 27$ GeV
	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$
Small-R jets ($R = 0.4$)	$p_T > 26$ GeV		Same as detector-level
	$\|\eta\| < 2.5$		
b-tagged jets ($R = 0.4$)	DL1r multivariate tagger at 77% efficiency		Jet ghost-matched to b-hadron
	≥ 1 b-tagged jet is constituent of top-jet		Same as detector-level
	≥ 1 b-tagged jet near lepton:	$\Delta R(\ell, b) < 2.0$	
		$\Delta R(t, b) > 1.0$	
Hadronic top-jet (t, $R = 1.0$)	**≥ 1 top-tagged large-R jet candidate**		Same as detector-level
($R = 0.4$ jets as input)	$p_T > 355$ GeV		
	$\|\eta\| < 2.0$		
	120 GeV $< m <$ 220 GeV		
	≥ 1 b-tagged sub-jet		
E_T^{miss} & m_T^W	$E_T^{miss} > 20$ GeV		Same as detector-level
	$E_T^{miss} + m_T^W > 60$ GeV		
Electron isolation	$\Delta R(e, t) > 1.0$		Same as detector-level
$m_{\ell b}$	$m_{\ell b} < 180$ GeV		Same as detector-level

Sample yields (pre-fit)

Events passing $m_{\text{top-jet}}$ selection:

- Selection criteria for large-R RC jets (slide 2),
- $135\text{ GeV} < m_{\text{top-jet}} < 205\text{ GeV}$

Sample	Yield
$t\bar{t}$	72000 ± 10000
Single-t	1290 ± 510
$t\bar{t}V$	740 ± 100
Multijet	450 ± 290
W+jets	310 ± 120
Z+jets	62 ± 31
Diboson	28 ± 14
Total pred	75000 ± 10000

Events passing m_{W} selection:

- Selection criteria for large-R RC jets (slide 2),
- $60\text{ GeV} < m_{\text{W}} < 105\text{ GeV}$,
- Require at least three sub-jets, $N_{\text{subjet}} \geq 3$.

Sample	Yield
$t\bar{t}$	38000 ± 5800
Single-t	420 ± 190
$t\bar{t}V$	330 ± 50
Multijet	170 ± 110
W+jets	59 ± 22
Z+jets	9 ± 5
Diboson	5 ± 3
Total pred	39000 ± 5800

Events passing $m_{t^{\text{lep}}+j}$ selection:

- $150\text{ GeV} < m_{t^{\text{lep}}+j} < 270\text{ GeV}$,
- $\Delta R(t^{\text{lep}}, j) < 0.5$,
- Need at least one extra jet, $N_{\text{addjets}} > 0$.

Sample	Yield
$t\bar{t}$	2340 ± 420
Single-t	53 ± 25
$t\bar{t}V$	51 ± 7
Multijet	23 ± 15
W+jets	21 ± 9
Z+jets	5 ± 3
Diboson	2 ± 1
Total pred	2500 ± 420

Note: These selections are not orthogonal

ATLAS work-in-progress