Measurements with highly boosted top quarks using the ATLAS detector

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on behalf of the ATLAS Collaboration

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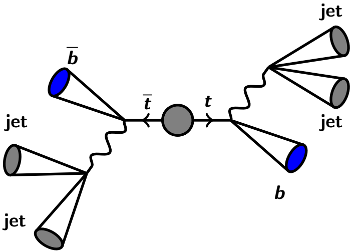
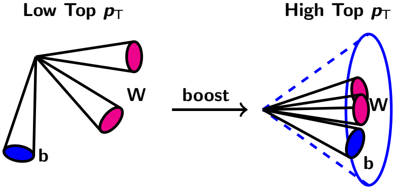
[1] ATLAS Collaboration, "Measurements of $t\bar{t}$ differential cross-sections of highly boosted top quarks decaying to all-hadronic final states in *pp* collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector", submitted to PRD.

[2] ATLAS Collaboration, "Measurements of top-quark pair differential cross-sections in the lepton+jets channel in *pp* collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector", JHEP 11 (2017) 191.

- New physics could alter top cross-sections especially in higher p_{T} phase spaces.
  - Top partners: SUSY, littlest Higgs, Kaluza-Klein excitations, etc.
- Boosted topologies probe QCD production of $t\bar{t}$.
- Boosted topologies aid in top triggering/reconstruction.
  - Triggering: fat jet trigger used in all-hadronic search.
  - Reconstruction: top daughters are collimated at boost $\rightarrow$ easier to identify.
    - Collimation reduces combinatorics.



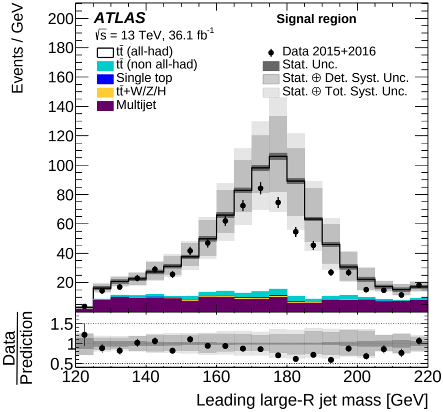


- Will cover 2 measurements:
  - Fully hadronic using 36 fb^{-1}.
  - Lepton+jets using 3.2 fb^{-1}.

0-lepton $t\bar{t}$ differential cross-section measurement with 36 fb^{-1}

Overview of 0-lepton channel

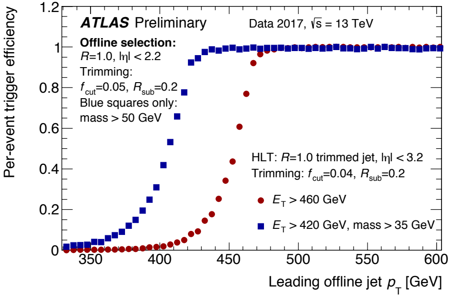
- Fully-hadronic top decay channel: boosted trigger is more efficient than multi-jet trigger in high top p_{T} topologies.
    - Ideal candidate for boosted triggers and methods.
- Dominant backgrounds are: multijet, semi-leptonic $t\bar{t}$.



Measure differential $t\bar{t}$ cross-section in various kinematic variables: top candidate p_{T}, top candidate rapidity (y), $t\bar{t}$ p_{T}, $t\bar{t}$ y, production angle, $\Delta\phi(t\bar{t})$

Boosted triggers

2017, with increased μ

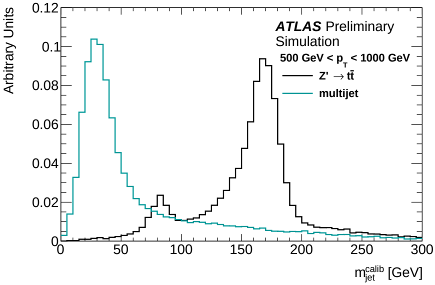


- Boosted jet trigger requires anti-k_t R=1.0 jets with $p_{\mathrm{T}} > 360$ GeV and $p_{\mathrm{T}} > 420$ GeV for 2015 and 2016.
    - Fully efficient at $p_{\mathrm{T}} > 480$ GeV: defines fiducial region.

Boosted trigger defines sensitive region: improvements to increase performance at higher μ will be essential for future results.

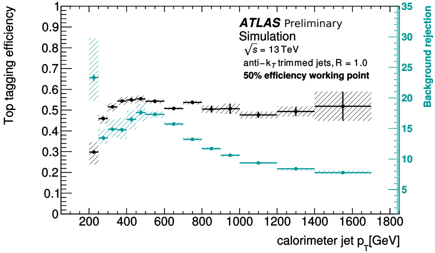
Top tagging

- Large-R jets are used as top candidates.
  - Trimmed: R=0.2 k_t sub-jets must have $p_\mathrm{T} > 0.05\times$ large-R jet p_T.
- Top tagging based on jet mass and N-subjettiness ratio, $\tau_{32} = \tau_3/\tau_2$ and binned p_T.



Performance of boosted top tagging directly impacts performance of cross section measurement.

Event selection



- Lepton veto: no muons or electrons with $p_T > 25$ GeV and $|\eta| < 2.5$.
- 2 large-R jets with $p_T > 350$ GeV, leading with $p_T > 500$ GeV.
- Leading 2 large-R jets must pass top tagging requirement.
  - 50% top-quark efficiency and rejection of 17 (10) of light quarks at $p_T \sim 500$ ($p_T > 1000$) GeV.
- b-jet must be associated with each top candidates ($\Delta R < 1.0$).

Results in 3451 events for differential cross-section measurements.

Background estimation technique

- Data driven background estimate used for multijet background, other background estimates based on MC.
- "ABCD" method that takes correlation into account used.
- Regions defined by number of b-jets and top-jets: SR has 2 b-jets and 2 top-jets.
- Control regions used for background estimates with validation regions close to SR.

2nd large-R jet				
1t1b	J (7.6%)	K (21%)	L (42%)	S
0t1b	B (2.2%)	D (5.8%)	H (13%)	N (47%)
1t0b	E (0.7%)	F (2.4%)	G (6.4%)	M (30%)
0t0b	A (0.2%)	C (0.8%)	I (2.2%)	O (11%)
	0t0b	1t0b	0t1b	1t1b

Leading large-R jet

$$N_{\text{bkg}} = \frac{J \times O}{A} \cdot \frac{D \times A}{B \times C} \cdot \frac{G \times A}{E \times I} \cdot \frac{F \times A}{E \times C} \cdot \frac{H \times A}{B \times I}$$

Systematic uncertainties

Source	Percentage
Large-R jet energy scale	5.9
Large-R jet mass calibration	1.4
Large-R jet top-tagging	12
Small-R jets	0.3
Pileup	0.6
Flavor tagging	8.3
Background	0.9
Luminosity	2.0
Monte Carlo statistical uncertainty	0.9
Alternative hard-scattering model	11
Alternative parton-shower model	14
ISR/FSR + scale	1.1
Total systematic uncertainty	24
Data statistical uncertainty	2.3
Total uncertainty	24

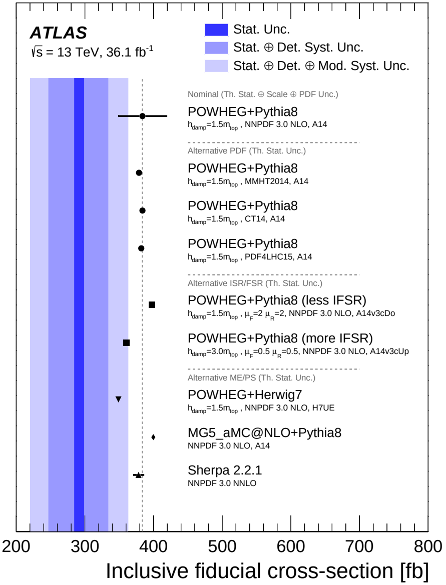
- Mass calibration = effect of mass resolution and scale (dominated by resolution).
- Dominant detector uncertainty: large-R top-tagging (τ_{32}, large-R jet mass).
- Dominant modelling uncertainty: hard-scattering/parton-shower modeling.
- Total uncertainty dominated by 24% systematic uncertainty.

Results: inclusive fiducial cross-section

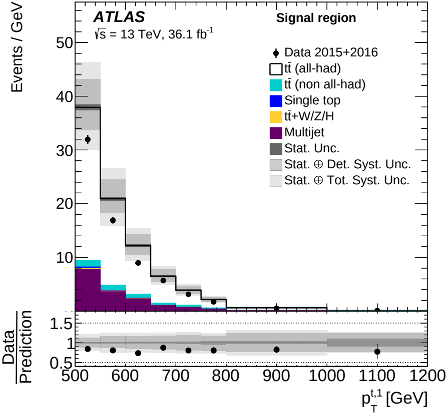
$t\bar{t}$ (all-hadronic)	3250 ± 470
$t\bar{t}$ (non-all-hadronic)	200 ± 40
Single-top-quark	24 ± 12
$t\bar{t}+W/Z/H$	33 ± 10
Multijet events	810 ± 50
Prediction	4320 ± 530
Data ($36.1\,\text{fb}^{-1}$)	3541

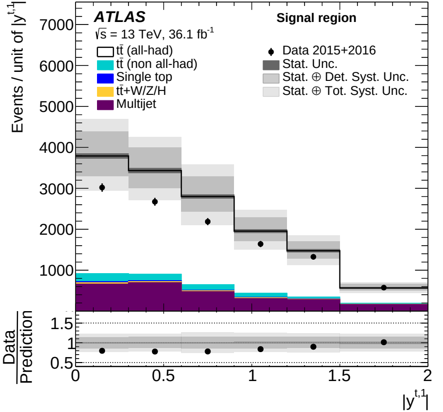
$$\sigma_{\text{fid}} = 292 \pm 7\ (\text{stat}) \pm 76\ (\text{syst})$$
$$\sigma_{\text{fid,Powheg+Pythia8}} = 384 \pm 36$$

- Predicted yields for various theory calculation over-estimate the cross-section.
- Significant systematic uncertainty $\rightarrow$ not statistically significant deviation.



Results: kinematic distributions

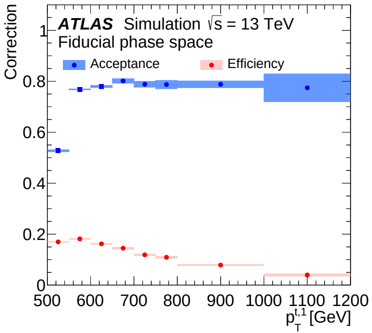


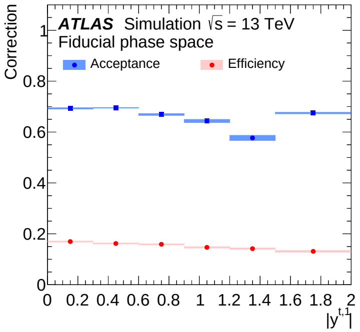


- Measured cross section in fiducial region as a function of many variables with sensitivity to new physics.
  - Top candidate: p_{T}, y
  - $t\bar{t}$ system: p_{T}, mass, y, H_{T}, $\Delta\phi(t_1, t_2)$, production angle in Colins-Soper reference frame, longitudinal boost, out-of-plane momentum, rapidity difference between tops.
- Compared to many theory calculations from NLO MC generators.

Unfolding

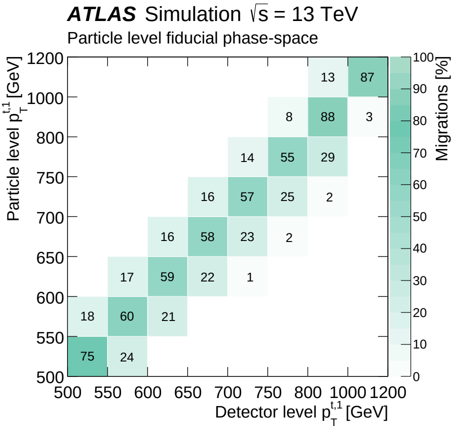
- Differential cross-sections in different variables done at particle and parton level.
  - Particle level = particle that interact with the detector after showering.
  - Parton level = matrix element particles.
- MC is used to correct for detector acceptance, efficiency, and resolution.
- Particle level objects are required to match detector objects.
  - Same requirements on p_T and $|\eta|$.
  - Object to object matching.
- Acceptance and efficiency corrections in bins of differential cross-section variables accounted for.

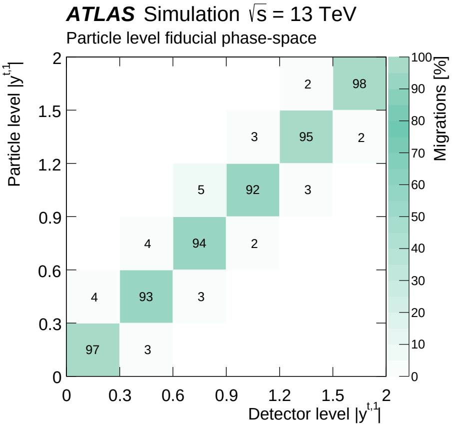




More on unfolding

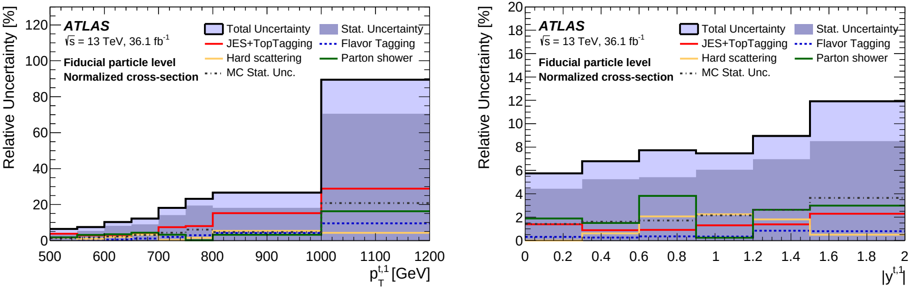
- Particle/parton level top jet/quark is matched ($\Delta R < 1.0$) to detector level large-R jet.
- Need to take bin-by-bin migration into account during unfolding.
- Done with migration matrix → filled using MC detector, particle, parton level variables.





No more than one bin migration in both p_{T} and rapidity.

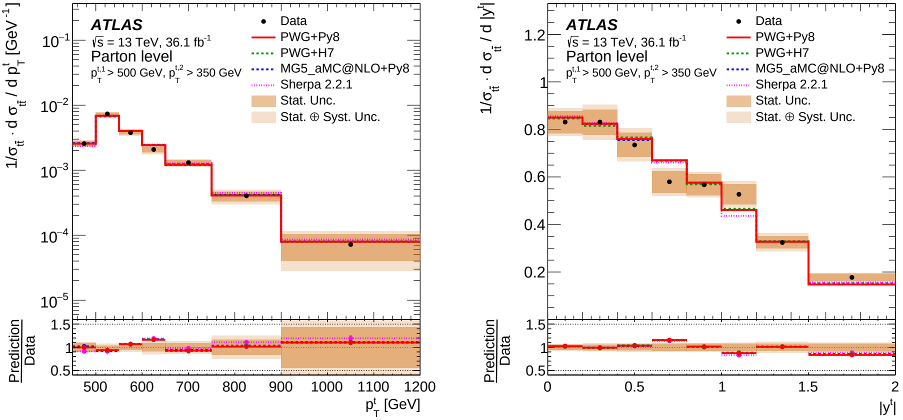
Systematic uncertainties in unfolding



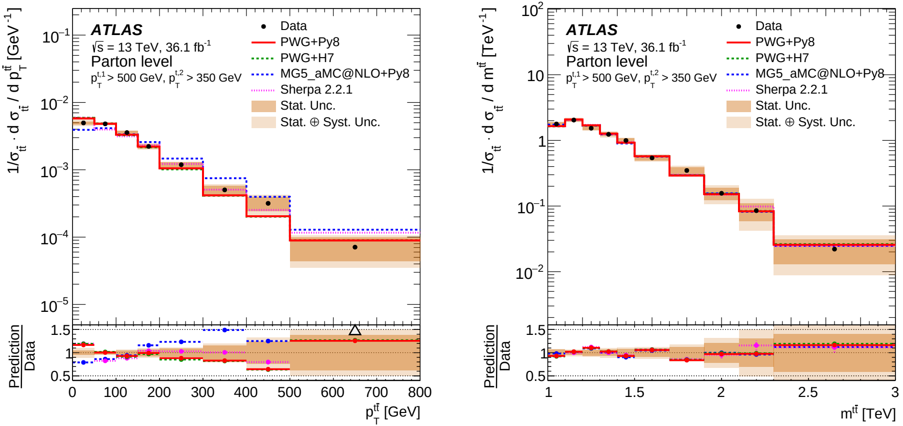
- Systematics are propagated to particle and parton level differential cross-section.
- Statistical uncertainty dominant for most $p_{\mathrm{T}}^{t,1}$ and $|y^{t,1}|$ bins.
- JES and top tagging uncertainty dominant systematic in $p_{\mathrm{T}}^{t,1}$.
- Hard scattering and parton shower are dominant systematics in $|y^{t,1}|$.

Unfolded results: top related variables

- Unfolded detector level result to parton level cross section.



- Average top quark kinematics shown.
- Calculated by choosing one top quark at random per event.

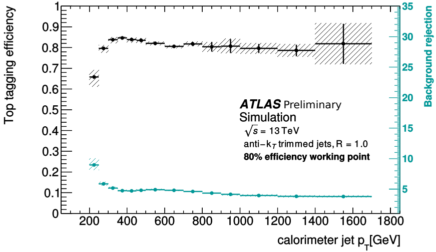


- χ^2 comparison performed for all normalized distribution.
  - Most detector uncertainties effect all bins equally $\rightarrow$ normalization helps cancel these effects.
- Most p-values lie between 0.15 and 0.55.
- Largest deviation (p-value < 0.01) comes in MG5_aMC@NLO+Pythia8 in $p_{\mathrm{T}}^{t\bar{t}}$, $\Delta\phi^{t\bar{t}}$, and $|p_{\mathrm{out}}^{t\bar{t}}|$.

One-lepton $t\bar{t}$ differential cross-section measurement with 3.2 fb^{-1} (boosted)

Overview of 1-lepton channel

- Trigger on muon or electron and combine muon and electron channel.
- Large-R jets are used as top candidates with $300 < p_{\mathrm{T}} < 1500$ GeV and $|\eta| < 2.0$.
- One top tag required, using the large-R mass and τ_{32} binned in p_{T}.
    - Top tagging requirement with 80% top efficiency is chosen.

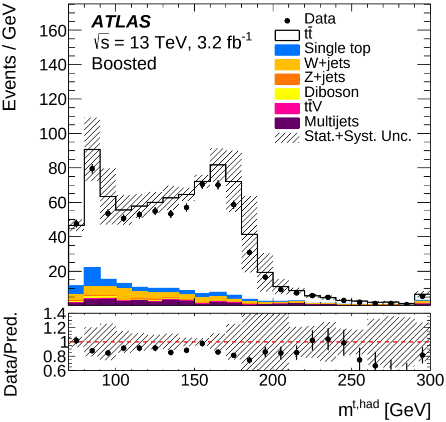


- Dominant backgrounds: single top, multijets, W+jets.

Event selection

- ΔR(lepton, small-R) < 2.0 and large-R jet must have $\Delta R > 1.5$ with small-R jet.
- A b-jet must be associated with large-R jet or with the lepton.
- $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}} + m_T^W > 60$ GeV.

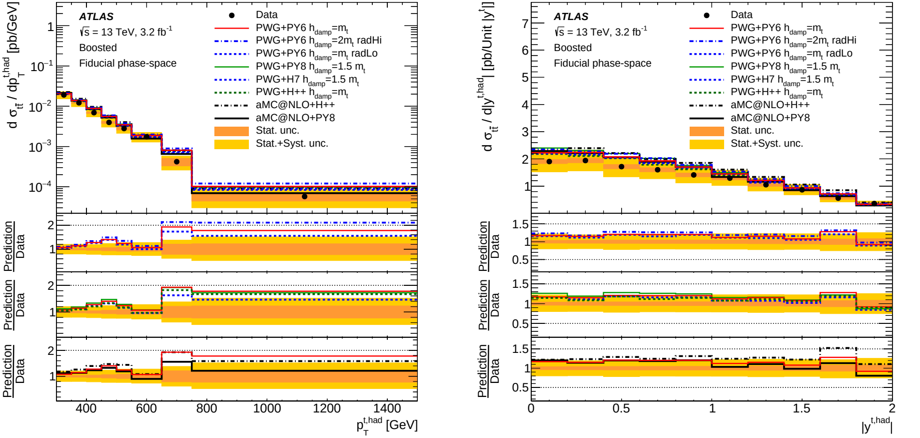
Process	Expected events
	Boosted
$t\bar{t}$	7000 ± 1100
Single top	500 ± 80
Multijets	300 ± 80
W+jets	500 ± 200
Z+jets	60 ± 40
$t\bar{t}V$	70 ± 10
Diboson	60 ± 10
Total prediction	8300 ± 1300
Data	7368



- Powheg+Pythia6 over predicts signal.
- 20-50% systematic uncertainty mainly from large-R jet uncertainties.

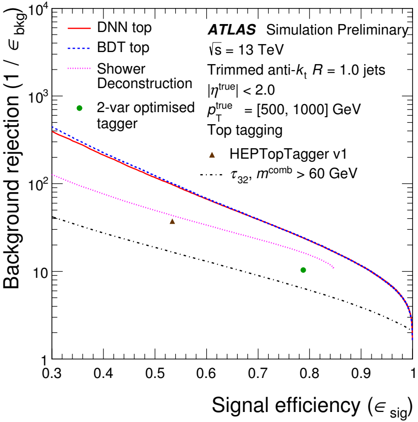
$$\sigma_{\text{fid}} = 2.54 \pm 0.54 \text{ (stat+syst)}$$
$$\sigma_{\text{fid,Powheg+Pythi6}} = 2.96$$
$$\sigma_{\text{fid,gen}} = 2.84\text{-}3.19$$

Unfolded results



- Comparisons between various generators: no generator described all distributions.
- Smallest p-values (0.01-0.05) are for Powheg+Pythia6 radHi, Powheg+Pythia8, and MG5_aMC@NLO+X.

Future prospects



- Improvements in boosted top triggers will increase sensitive region.
- Improved top taggers. See talk by A. Søgaard.
  - Machine learning (deep neural networks and boosted decision trees) combine many variables and deal with their correlations.
- Improved calibrations will reduce systematics from mass/p_T resolution. See talk by A. Arce. and S. Ganguli.

Summary

- Measured total fiducial and differential cross-section in all-hadronic and lepton+jets channel.
  - Detector, particle and parton level measurement.
  - In many variables: leading top p_{T}, rapidity, $t\bar{t}$ p_{T}, $t\bar{t}$ rapidity, production angle, etc.
- Boosted top tag played an essential role in sensitivity to high top p_{T} kinematic phase space.
- No significant deviation found from theory prediction in total and differential cross-section.
  - But large uncertainties due to hard scattering and parton showering models.
- Differential cross-section showed some poor agreement in $t\bar{t}$ system variables for some generators.