

Single top quark cross sections at ATLAS

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Introduction and motivation: single top

Production via weak interaction—opportunity to study tWb vertex

Cross-section measurements: tests of QCD calculations, Monte Carlo modeling

t -channel (tq) production

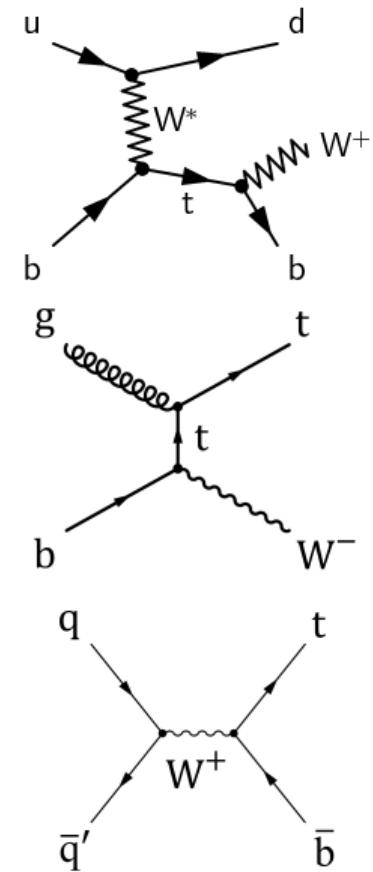
Largest cross-section and cleanest signal of single-top processes—best measurement of $|V_{tb}|$, test of PDF models, pQCD tests

tW production

Anomalous couplings in the tWb vertex may arise in some BSM models— tb and tq are sensitive to different couplings than tW

s -channel (tb) production

Very small cross-section at LHC, challenging to measure



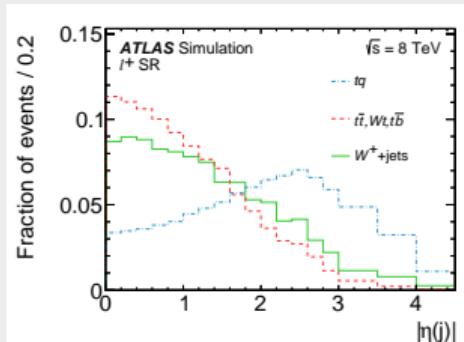
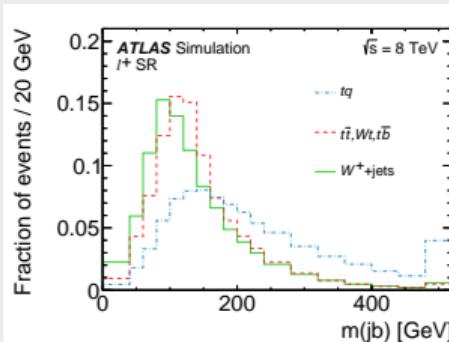
Analysis of **total**, **fiducial**, and **differential** *t*-channel cross-sections

Use leptonic *W* decays \rightarrow lepton+jets channel

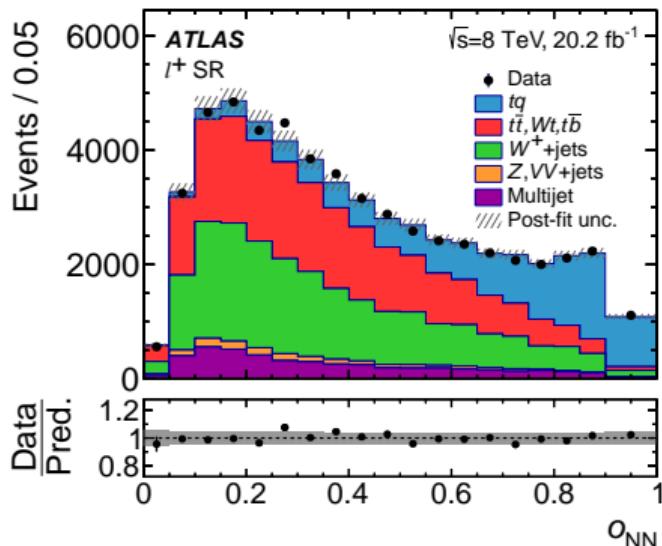
Events have light-flavor **forward jet** from the “spectator” quark

Require *b*-jet, E_T^{miss} , and m_T^W to suppress **multi-jets** background

Top-ranked NN inputs



Neural network combining 7 inputs variables, discriminant shown below



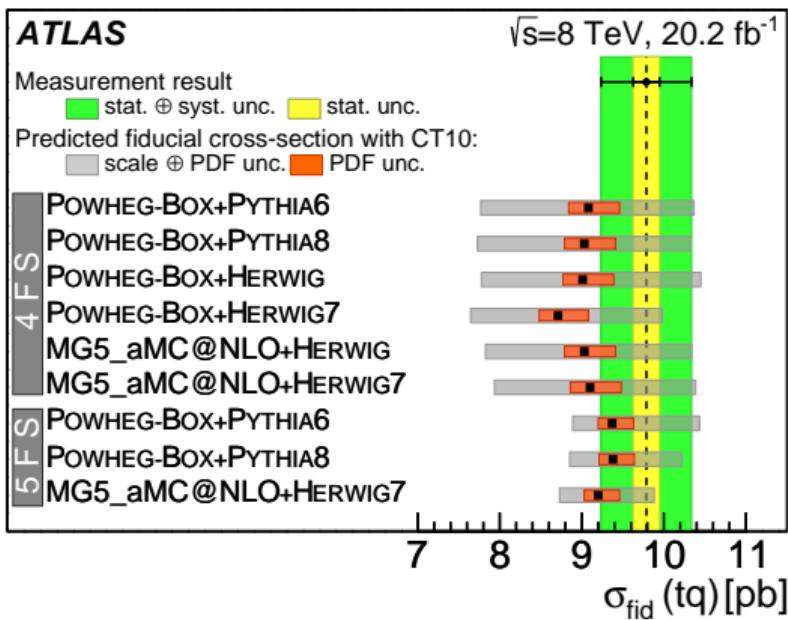
Largest backgrounds are $t\bar{t}$ and $W + \text{jets}$

Uncertainties on fiducial cross-sections are generally spread **evenly** among sources c.f. previous measurements, in [ATLAS-CONF-2014-007](#) and [ATLAS-CONF-2012-132](#) jet energy scale (JES) and t -channel model uncertainties were dominant

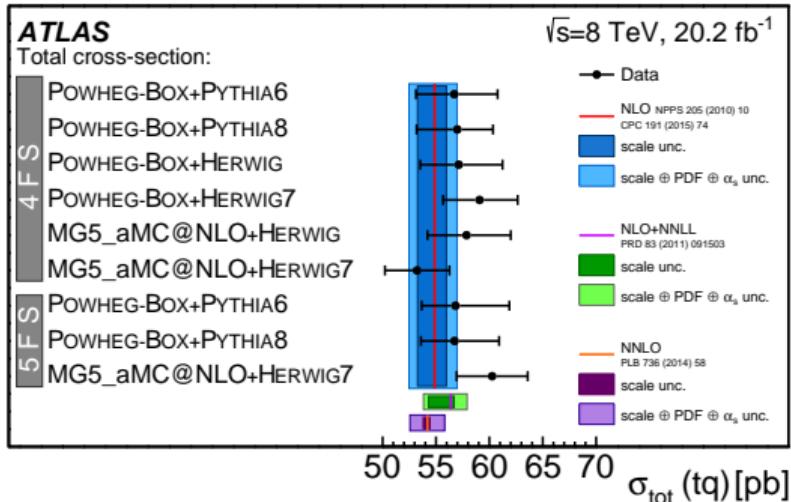
Largest uncertainties are lepton reco., JES, background $t\bar{t}$ NLO matching model

Source	$\Delta\sigma_{\text{fid}}(tq) / \sigma_{\text{fid}}(tq)$ [%]	$\Delta\sigma_{\text{fid}}(\bar{t}q) / \sigma_{\text{fid}}(\bar{t}q)$ [%]
Data statistics	± 1.7	± 2.5
Monte Carlo statistics	± 1.0	± 1.4
Background normalisation	< 0.5	< 0.5
Background modelling	± 1.0	± 1.6
Lepton reconstruction	± 2.1	± 2.5
Jet reconstruction	± 1.2	± 1.5
Jet energy scale	± 3.1	± 3.6
Flavour tagging	± 1.5	± 1.8
E_T^{miss} modelling	± 1.1	± 1.6
b/\bar{b} tagging efficiency	± 0.9	± 0.9
PDF	± 1.3	± 2.2
tq ($\bar{t}q$) NLO matching	± 0.5	< 0.5
tq ($\bar{t}q$) parton shower	± 1.1	± 0.8
tq ($\bar{t}q$) scale variations	± 2.0	± 1.7
$t\bar{t}$ NLO matching	± 2.1	± 4.3
$t\bar{t}$ parton shower	± 0.8	± 2.5
$t\bar{t}$ scale variations	< 0.5	< 0.5
Luminosity	± 1.9	± 1.9
Total systematic	± 5.6	± 7.3
Total (stat. + syst.)	± 5.8	± 7.8

Fiducial cross-section measured in region defined by particle-level observables, close to reco. event acceptance:
1 charged lepton, 2 jets (1 *b*-tagged),
 $m(\ell b) > 160$ GeV

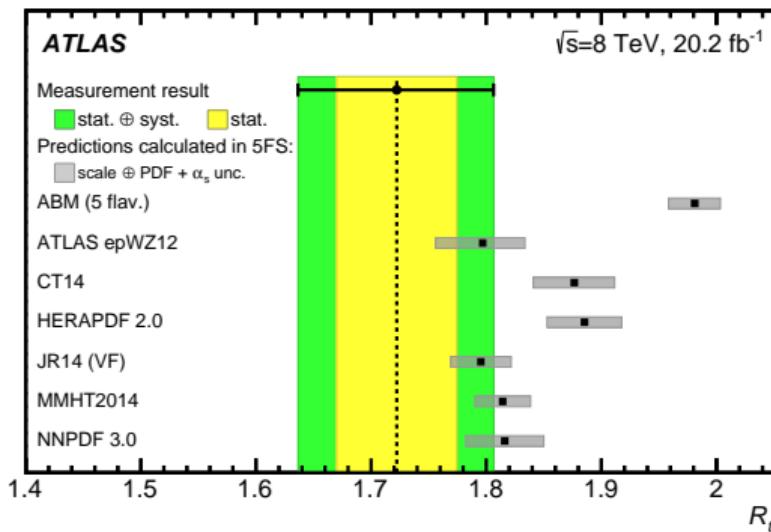


Total cross-section extrapolated to full phase-space, compared to fixed-order calculations



Ratio of t to \bar{t} cancels many uncertainties, can better distinguish PDF predictions

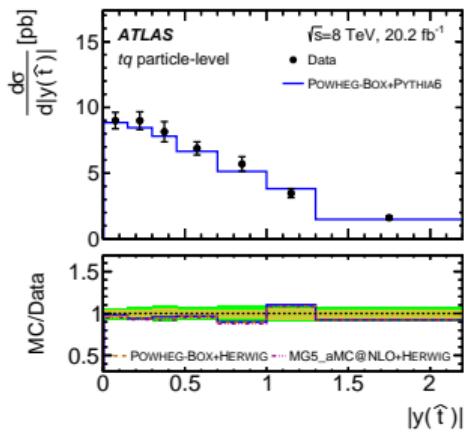
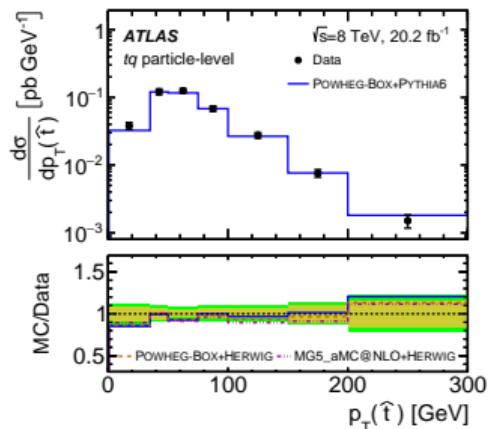
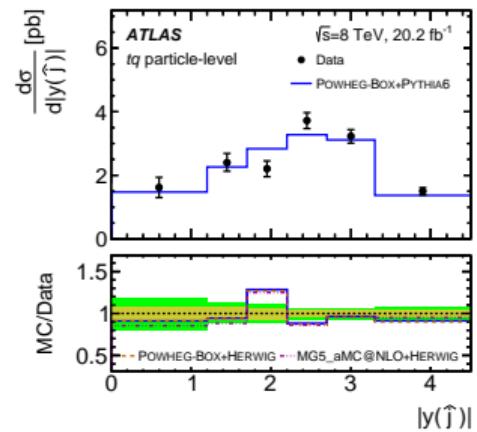
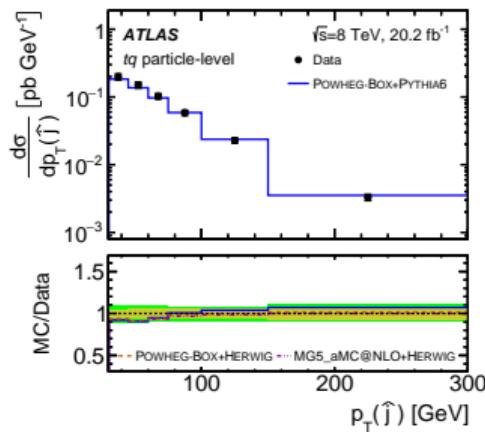
Uncertainties on R_t dominated by **statistics**, $t\bar{t}$ MC model



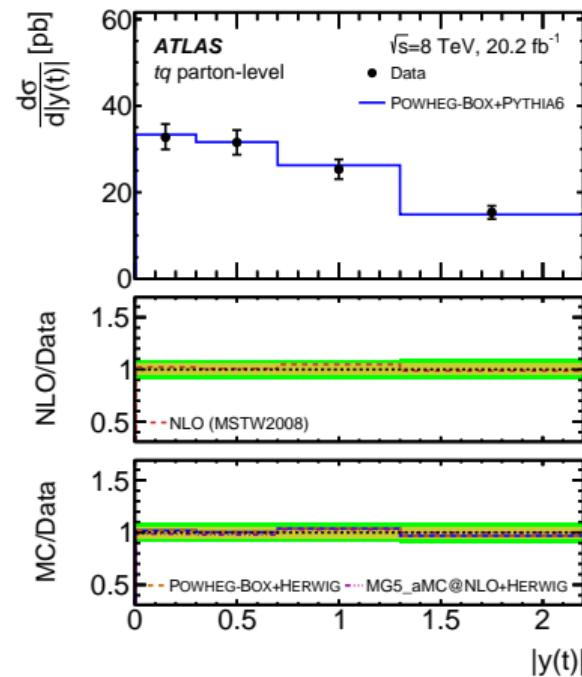
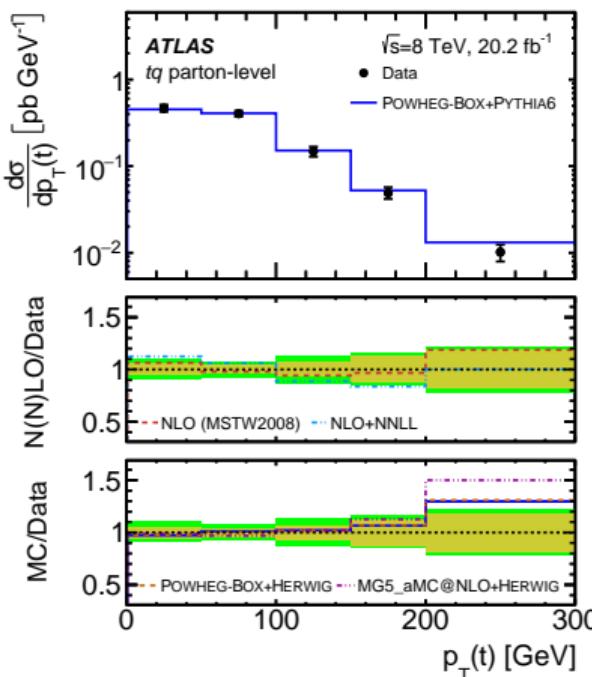
Source	$\Delta R_t / R_t [\%]$
Data statistics	± 3.0
Monte Carlo statistics	± 1.8
Background modelling	± 0.7
Jet reconstruction	± 0.5
E_T^{miss} modelling	± 0.6
tq ($\bar{t}q$) NLO matching	± 0.5
tq ($\bar{t}q$) scale variations	± 0.7
$t\bar{t}$ NLO matching	± 2.3
$t\bar{t}$ parton shower	± 1.7
PDF	± 0.7
Total systematic	± 3.9
Total (stat. + syst.)	± 5.0

Differential measurements in fiducial (particle-level) and full (parton-level) phase space, using events with $\mathcal{O}_{NN} > 0.8$

Distributions of $p_T(\hat{t})$, $|y(\hat{t})|$, $p_T(j)$, and $|y(j)|$ measured at **particle-level** and $p_T(t)$, $|y(t)|$ at parton-level



Distributions of $p_T(\hat{t})$, $|y(\hat{t})|$, $p_T(j)$, and $|y(j)|$ measured at particle-level and $p_T(t)$, $|y(t)|$ at **parton-level**

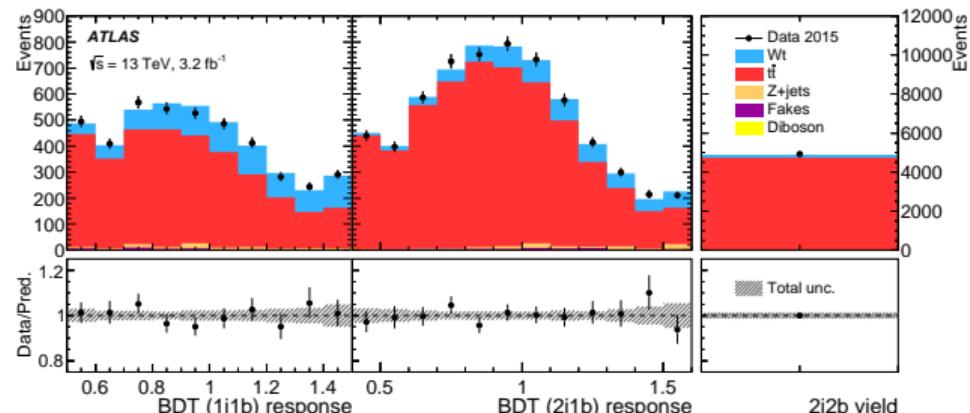
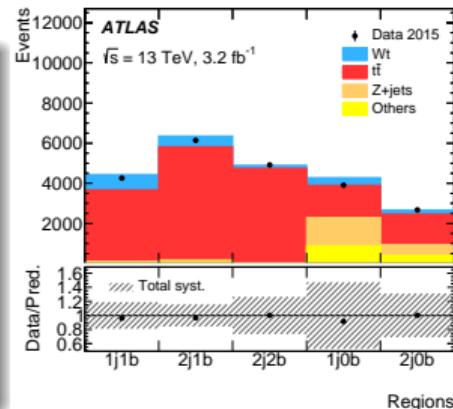


Overview/Strategy

- First look at tW in new kinematic regime
- Dilepton final state
- BDT to separate tW signal from $t\bar{t}$ background, based on momenta of leptons, jet, E_T^{miss}
- Profile likelihood fit to BDT discriminant in 3 regions

ATLAS analysis of 3.2 fb^{-1}
data at $\sqrt{s} = 13$ TeV

BDT in 1j1b, 2j1b region,
single bin for 2j2b



Result

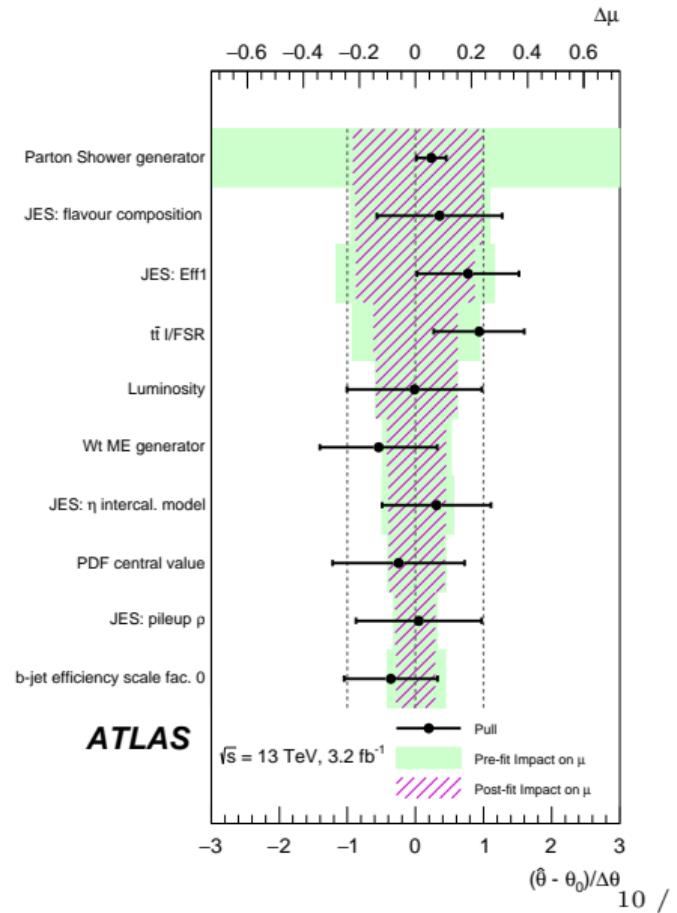
$$\sigma_{\text{obs}} = 94 \pm 10(\text{stat})^{+28}_{-22}(\text{syst}) \pm 2(\text{lumi}) \text{ pb}$$

$$\sigma_{\text{appx. NNLO}} = 71.7 \pm 3.9 \text{ pb}$$

Kidonakis, [PRD 82 \(2010\) 054018](#)

Highest-impact uncertainties are tW parton shower generator, JES, ISR/FSR ($t\bar{t}$)

Fit is able to significantly constrain uncertainties from PS generator, ISR/FSR

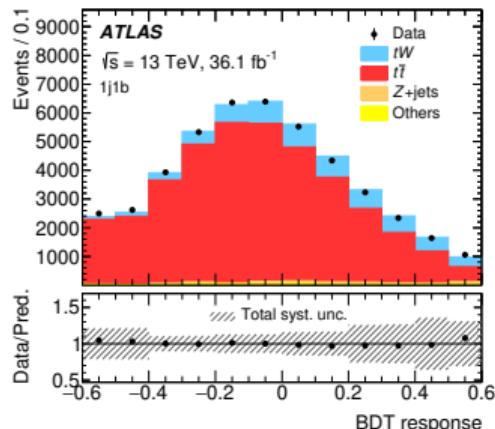


Overview

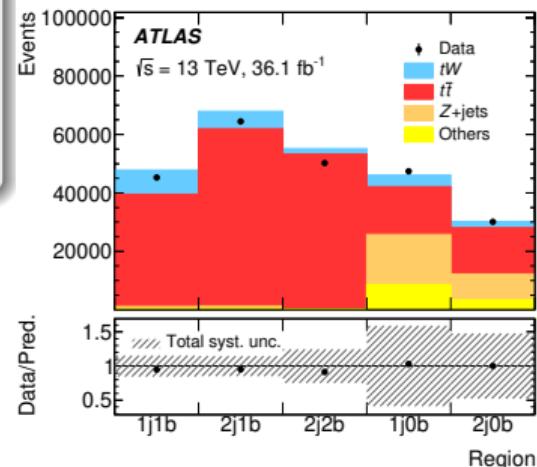
Based on [arXiv:1612.07231](https://arxiv.org/abs/1612.07231) inclusive tW cross-section measurement:

- Dilepton final state
- **BDT** to separate tW from $t\bar{t}$ background

Unfold with **iterative Bayesian** method



ATLAS analysis of 36.1 fb^{-1} data at $\sqrt{s} = 13$ TeV

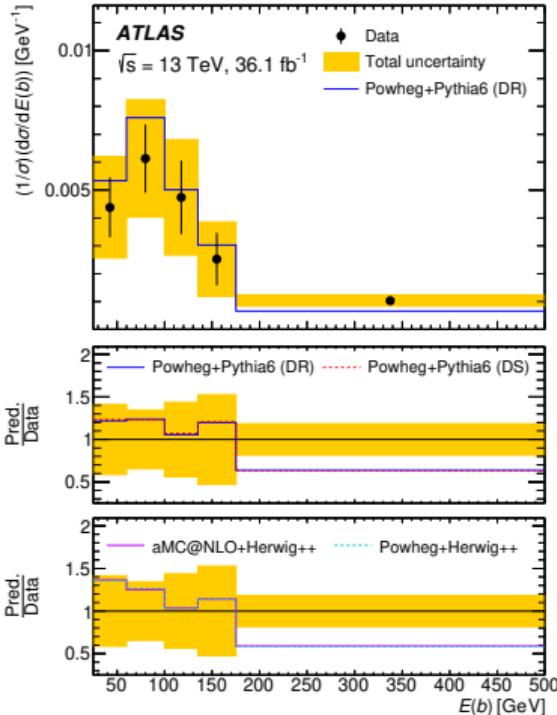


Only the 1j1b region is used in this analysis, others are kept for validation only

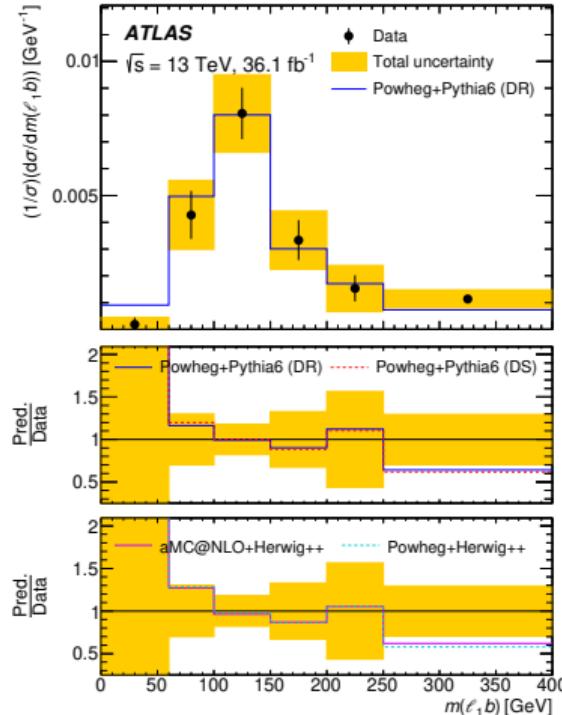
Normalised differential cross-sections

EPJC (submitted)

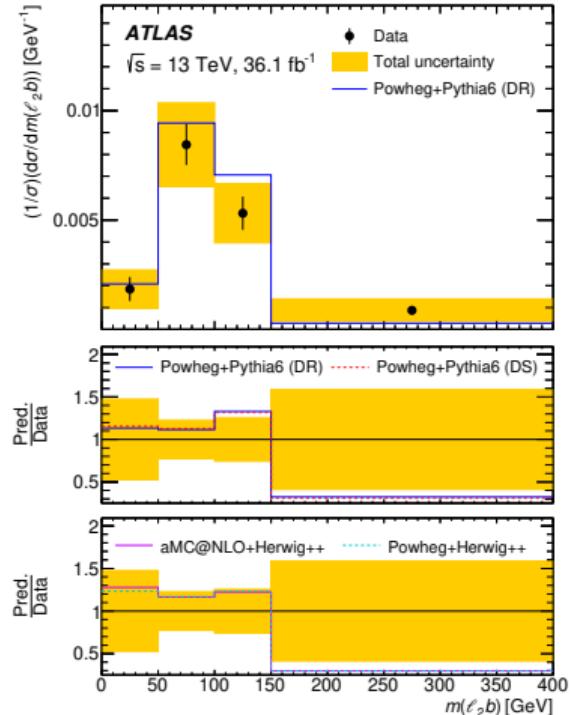
$E(\ell_1 \ell_2 b)$



$m_T(\ell_1 \ell_2 \nu b)$



$m(\ell_1 \ell_2 b)$

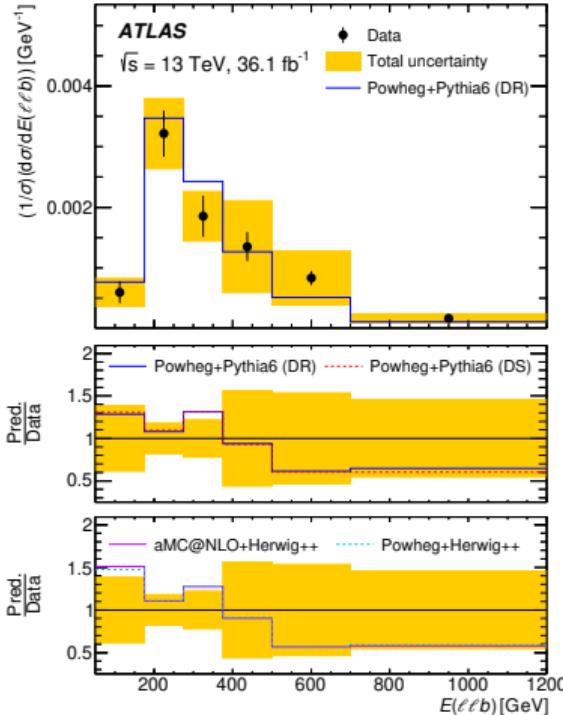


$t\bar{t}$ and tW MC models are largest sources of uncertainty

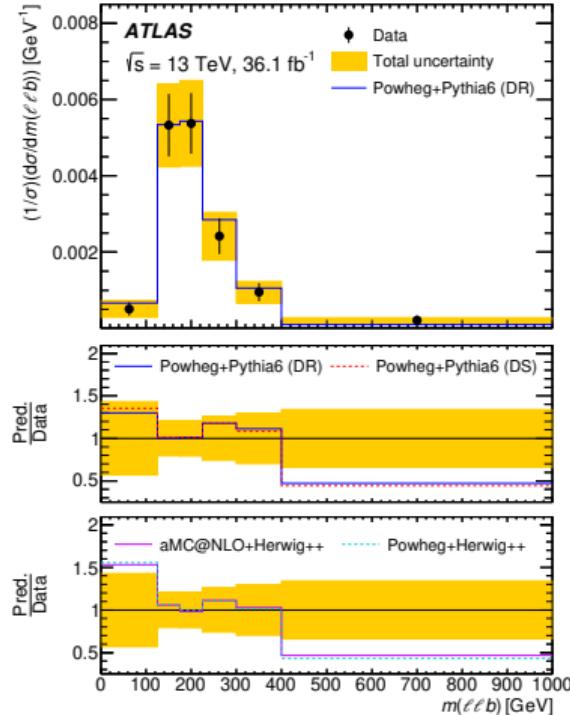
Normalised differential cross-sections

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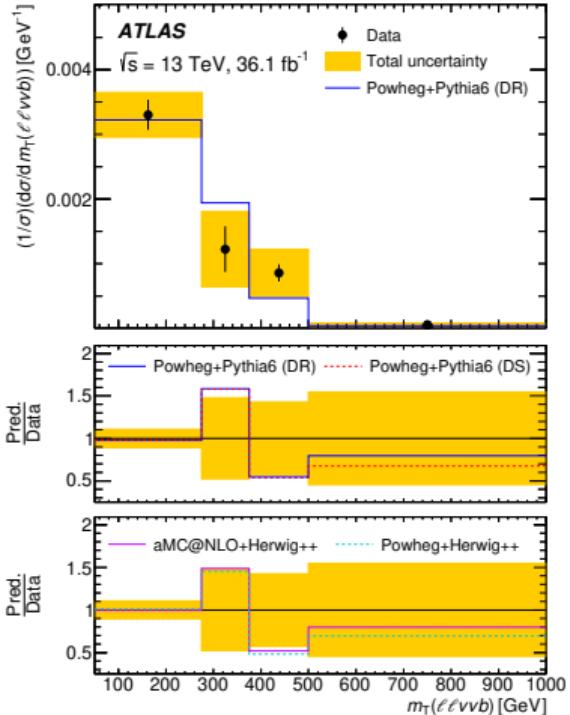
$m(\ell_1 b)$



$m(\ell_2 b)$



$p_T^{\text{sys}}(\ell_1 \ell_2 \nu b)$



Possibly an indication that some MC distributions are too “soft”

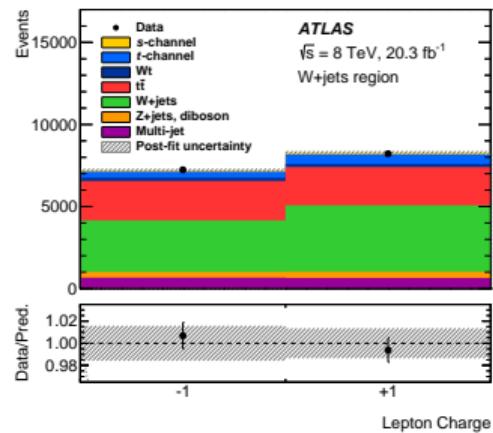
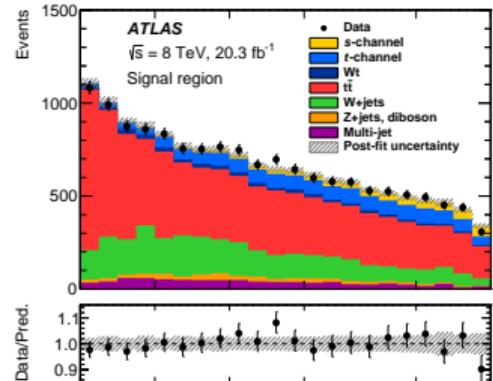
ATLAS Analysis of 20.3 fb^{-1} of $\sqrt{s} = 8$ TeV data

Overview/Strategy

- Lepton+jets events selected and classified into 2j2b (signal), 2j1b (tq , W +jets)
- Matrix element method employed to separate tb signal from backgrounds
- Combined likelihood fit to in signal region (ME discriminant) and control region (lepton charge)

Lepton charge distribution in control region provides a straightforward way to discriminate W +jets from other processes

Data driven estimate used for multi-jet events, others normalized by theory predictions and constrained in fit



Signal strength, nuisance parameters from systematic and MC statistical uncertainties estimated from likelihood fit

Results

$$\sigma_{\text{obs}} = 4.8 \pm 0.8(\text{stat})^{+1.6}_{-1.3}(\text{syst})\text{pb}$$

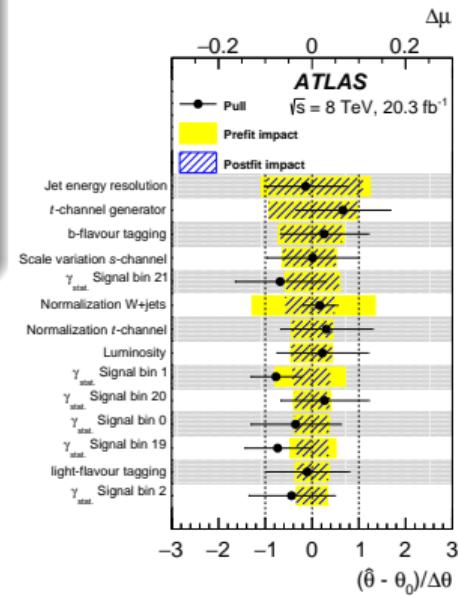
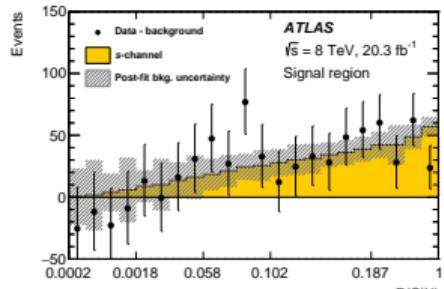
$$\sigma_{\text{NLO+NNLL}} = 5.24^{+0.22}_{-0.20}\text{pb}$$

HATHOR calculation, [CPC 182 \(2011\) 1034-1046](#)

Signal significance observed (expected): 3.2σ (3.9σ)

Highest-impact uncertainties are jet energy resolution, tq , tb
MC model, flavor tagging

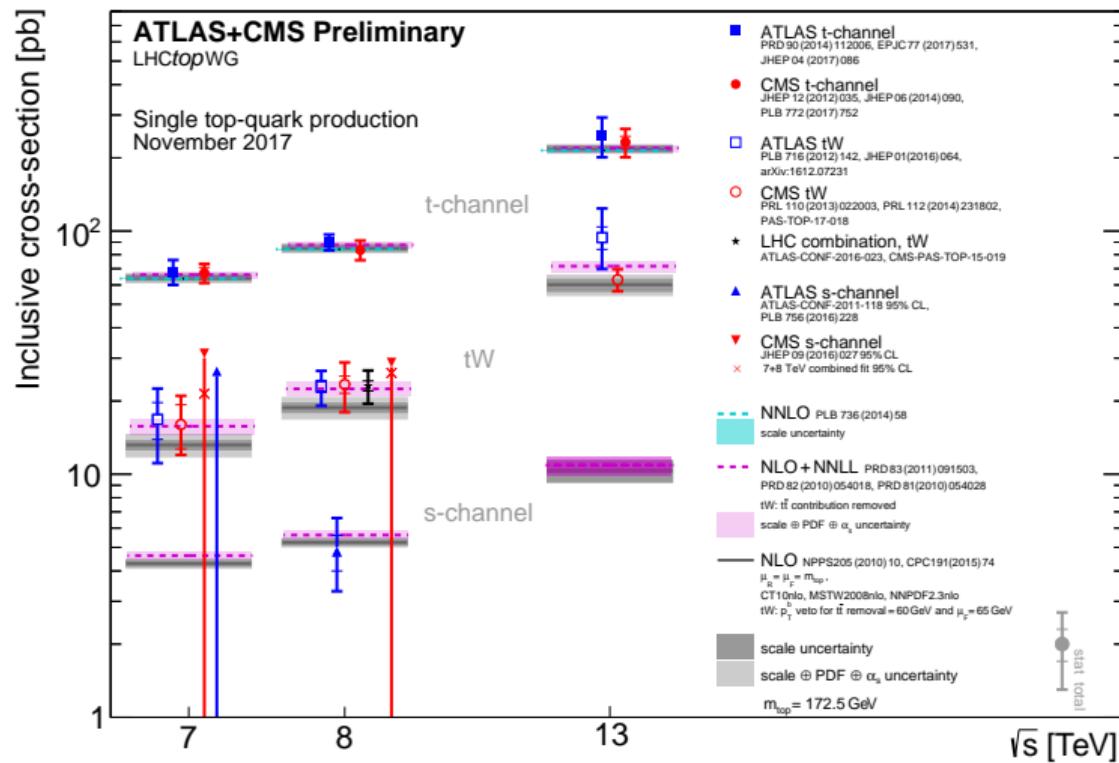
Uncertainty from $W +$ jets background normalization is
constrained from use of control region in fit



Summary

Many new results still coming with run-1 and run-2 data from ATLAS

Future results with $\approx 100 \text{ fb}^{-1}$ run-2 data will continue to improve precision—better constraints from data, leverage better understanding of MC models to improve measurements



- Backup

Unfolding: choice of binning

Binning goals

- **Stable:** $\sim 60\%$ of entries on the diagonal
- **Balanced:** $\lesssim 20\%$ statistical uncertainty per bin

Binning procedure

- Identical for particle and reco levels (negligible bias)
- First and last bins chosen based on statistical uncertainty
- Other bins are a **multiple of the resolution** of the variable in question

Separating the $t\bar{t}$ background

- Almost entirely $Wt+t\bar{t}$ (1j1b bin)
- We use a **Boosted Decision Tree** (TMVA)
- Inputs are kinematic variables of subsets of objects plus some whole-event variables
- Procedure to narrow down the list:
 - ① rank variables by **separation power**
 - ② remove highly-correlated variables
 - ③ find combinations with best separation
 - ④ tie-break by preferring fewer variables

$$\langle S^2 \rangle = \frac{1}{2} \int \frac{(Y_S(y) - Y_B(y))^2}{(Y_S(y) + Y_B(y))} dy$$

- **Cut** on BDT output value of 0.3
(optimized to minimise the total)

Variable	$S [10^{-2}]$
$p_T^{\text{sys}}(\ell_1 \ell_2 E_T^{\text{miss}} j_1)$	4.1
$\Delta p_T(\ell_1 \ell_2 j_1, E_T^{\text{miss}})$	2.5
$\sum E_T$	2.3
$\eta(\ell_1 \ell_2 E_T^{\text{miss}} j_1)$	1.3
$\Delta p_T(\ell_1 \ell_2, E_T^{\text{miss}})$	1.1
$p_T^{\text{sys}}(\ell_1 \ell_2 j_1)$	1.0
$C(\ell_1 \ell_2)$	0.9
$m(\ell_2, j_1)$	0.2
$m(\ell_1, j_1)$	0.1

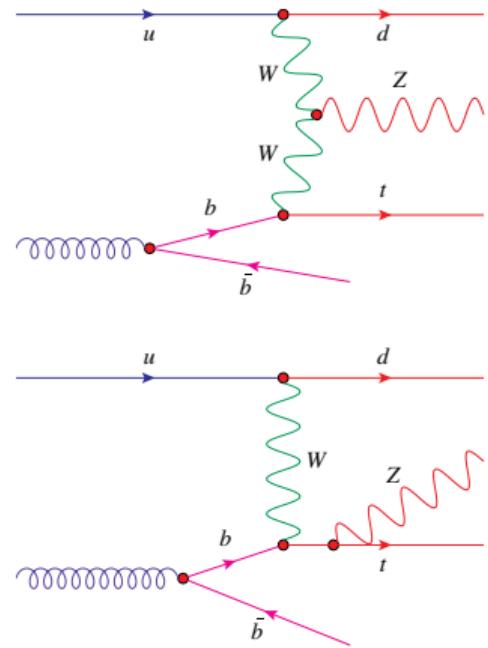
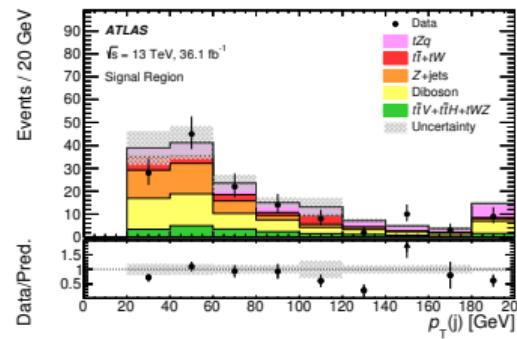
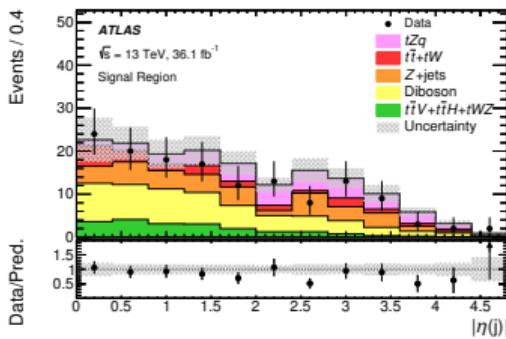
p_T^{sys} is the vectorial sum of p_T ;
 C is centrality (scalar sum of $p_T / \Sigma E$)

SM single top with Z not yet observed

SM tZq probes tZ and WWZ couplings, important background for tH and tZ FCNC production

Trilepton final state: 2.2% BR, but cleanest signal

Neural network trained using 10 variables, top 2 shown below



Maximum likelihood fit performed on NN output distribution

Observed significance 4.2σ (expected 5.4σ)

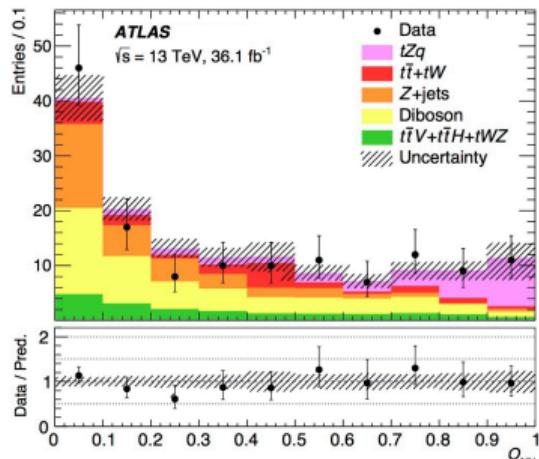
Results

$$\sigma_{\text{obs}} = 600 \pm 170(\text{stat.}) \pm 140(\text{syst.}) \text{ fb}$$

$$\sigma_{\text{NLO}} = 800^{+49}_{-59} \text{ fb}$$

MADGRAPH calculation, [JHEP 07 \(2014\) 079](#)

Clear evidence of SM tZq production in trilepton channel

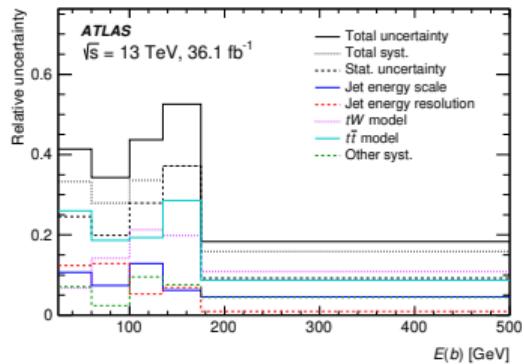


Source	Uncertainty [%]
tZq radiation	± 10.8
Jets	± 4.6
b -tagging	± 2.9
MC statistics	± 2.8
Luminosity	± 2.1
Leptons	± 2.1
tZq PDF	± 1.2
E_T^{miss}	± 0.3

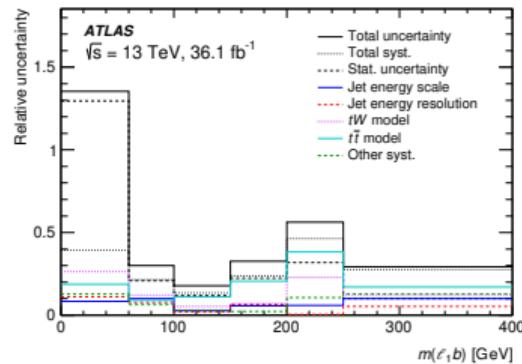
Uncertainties on norm. diff. cross-sections

EPJC (submitted)

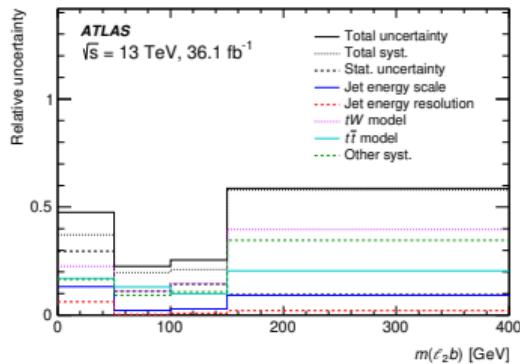
$E(\ell_1 \ell_2 b)$



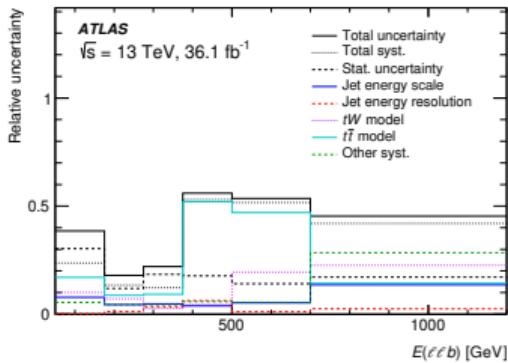
$m_T(\ell_1 \ell_2 \nu b)$



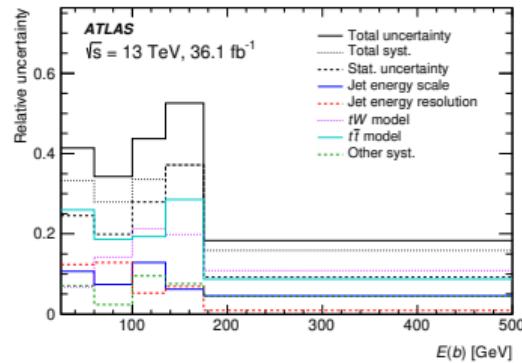
$m(\ell_1 \ell_2 b)$



$m(\ell_1 b)$



$m(\ell_2 b)$



$p_T^{\text{sys}}(\ell_1 \ell_2 \nu b)$

