Recent Single Top Quark Results at ATLAS

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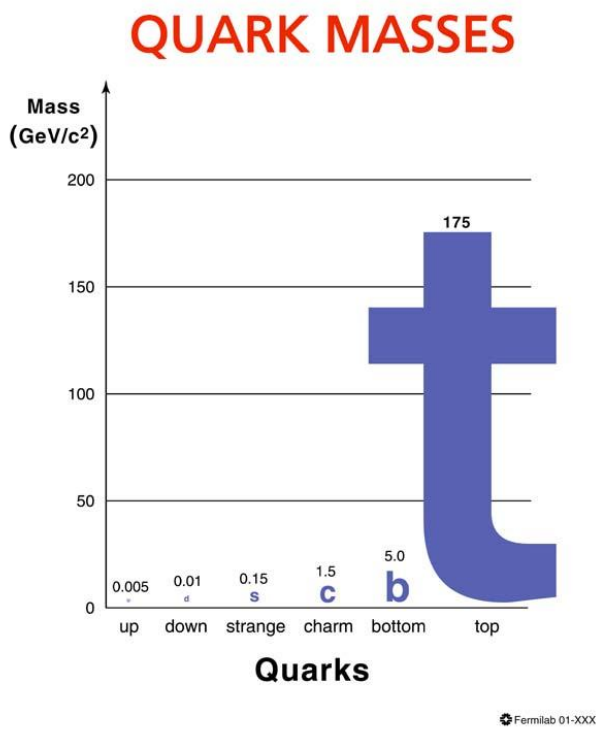
The top quark - why study it?

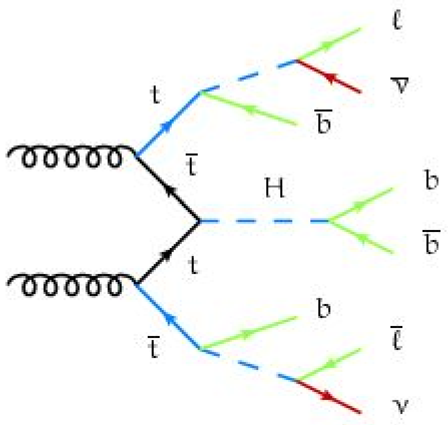
Discovered in 1995… the top quark is the **most massive** elementary particle… by a large margin!

As a consequence, the top quark **decays** before it can form hadrons- thus we can study the properties of a bare quark

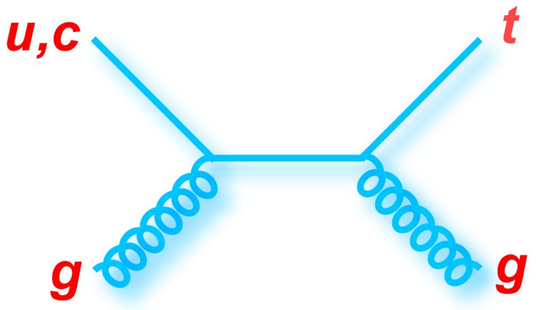


The top quark - why study it?

The coupling of the top to the **Higgs** is very large- measuring it may give hints about the **energy scale** of new physics

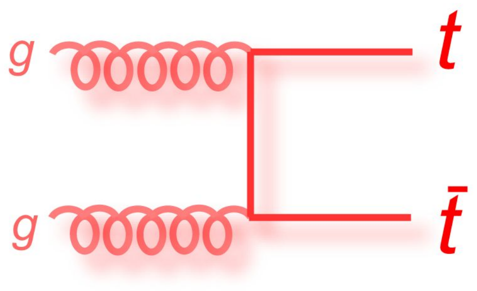


Potential for couplings to **new, undiscovered** particles is significant - need to look for small changes in expected rates of production

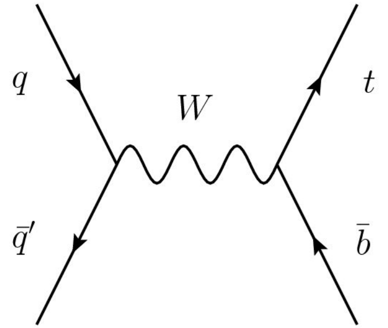


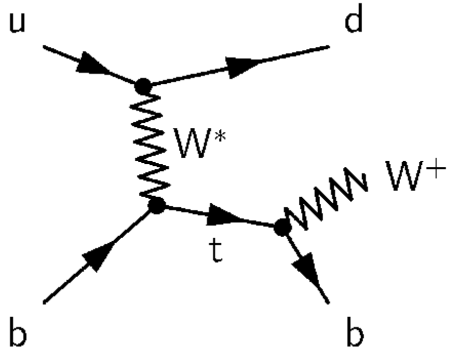
Top quarks in collisions

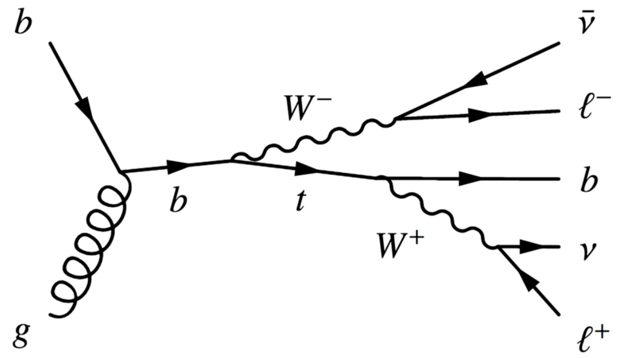
Top quark production may proceed by **pair production** or **single-top** production



Pair production via gluon fusion





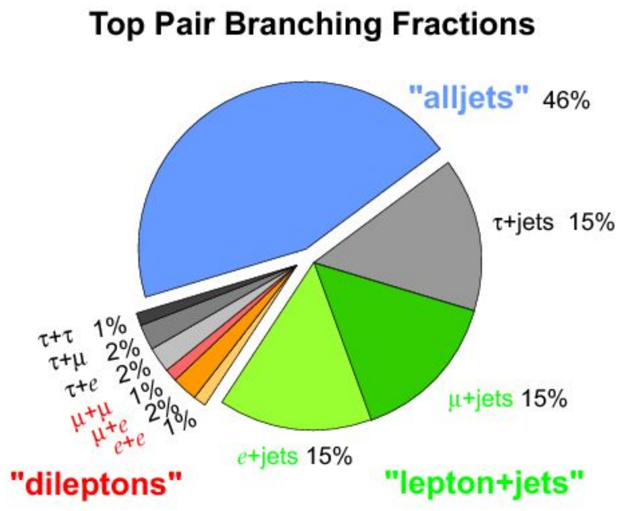


Single top production in the *s*-channel, *t*-channel, and associated *Wt* production

Top quarks in collisions

The top quark decays >99% of the time into a ***W* boson** and ***b* quark**

Analysis channels are defined by the **subsequent decay** of the *W*: **leptonic** or **hadronic**

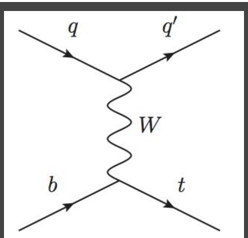


The ATLAS results

In this talk I'll present 3 recent results related to single top quark production:

- *t*-channel cross-section 13 TeV
  - Submitted 2016/09/13 to JHEP
- *t*-channel cross-section 8 TeV
  - Submitted 2017/02/09 to EPJC
- *Wt* cross-section 13 TeV
  - Submitted 2016/12/21 to JHEP

t-channel 13 TeV cross-section



Submitted to JHEP
3.2 fb^{-1}
2015
$\sqrt{s}$=13 TeV

Analysis of inclusive *t*-channel cross-sections for single top and anti-top quarks

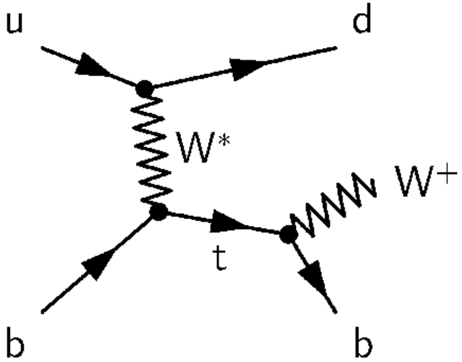
Tests of **NLO calculations** in new kinematic range, test of **PDF models**

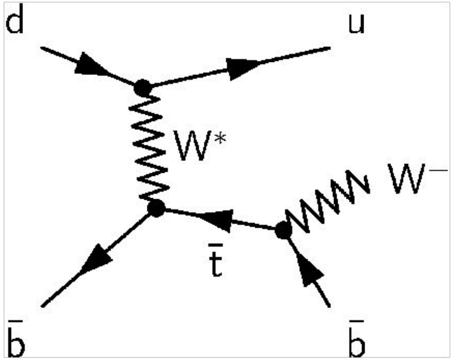
Measure properties of ***Wtb* vertex**, measure V_{tb} element of **CKM matrix**

Predicted cross-section at NLO:

$\sigma(tq) = 136.0^{+5.4}_{-4.6}$ pb and

$\sigma(\bar{t}q) = 81.0^{+4.1}_{-3.6}$ pb





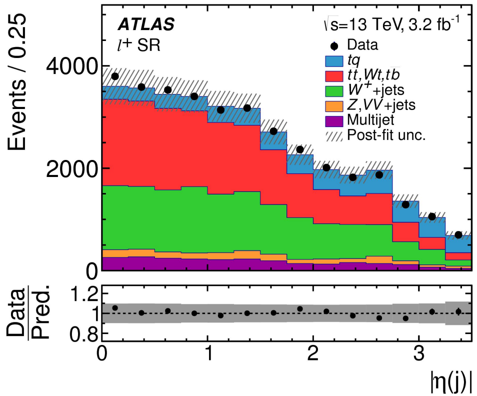
t-channel 13 TeV: event selection

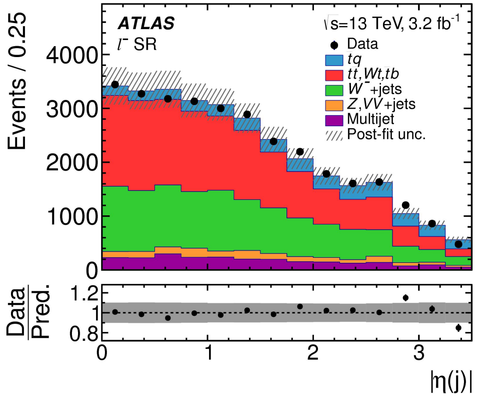
Use **leptonic *W*** decays-> **lepton+jets** channel

Events are characterised by a light-flavour **forward jet** from the “spectator” quark

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

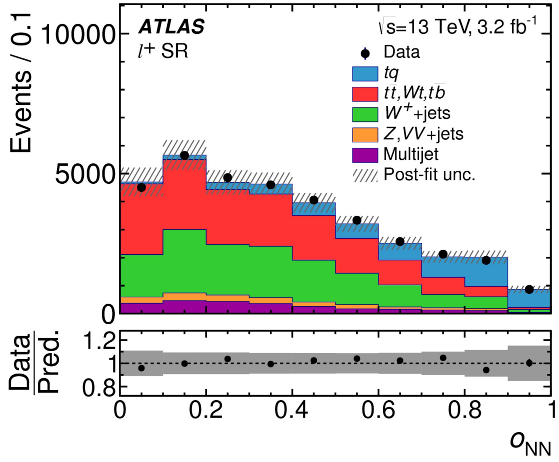
Define additional **validation regions** for *W*+jets (relaxed *b*-tag eff.) and top pair production (extra *b*-jet)

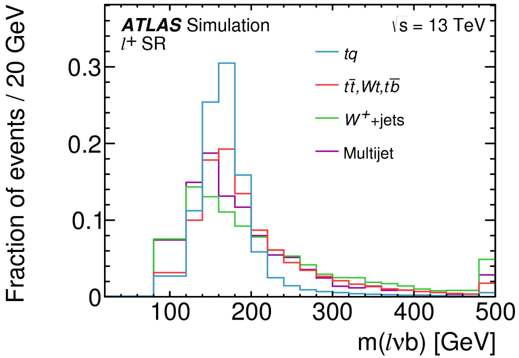


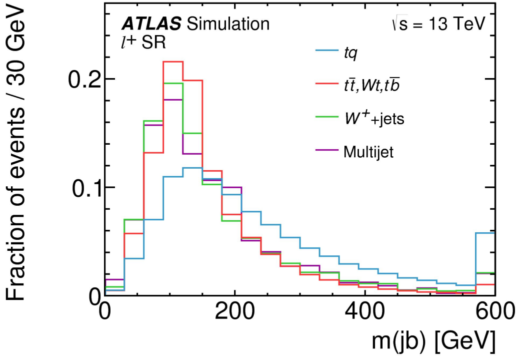


t-channel 13 TeV: neural network

- **Neural network** combining kinematic variables shown in table
- Several inputs rely on kinematic reconstruction of neutrino momenta, based on *W* mass assumption







Variable	Definition
$m(\ell\nu b)$	top-quark mass reconstructed from the charged lepton, neutrino, and b-tagged jet
$m(jb)$	invariant mass of the b-tagged and untagged jet
$m_{\mathrm{T}}(\ell E_{\mathrm{T}}^{\mathrm{miss}})$	transverse mass of the reconstructed W boson
$\lvert\eta(j)\rvert$	modulus of the pseudorapidity of the untagged jet
$m(\ell b)$	invariant mass of the charged lepton (ℓ) and the b-tagged jet
$\eta(\ell\nu)$	rapidity of the reconstructed W boson
$\Delta R(\ell\nu b, j)$	ΔR of the reconstructed top quark and the untagged jet
$\cos\theta^*(\ell, j)$	cosine of the angle θ^* between the charged lepton and the untagged jet in the rest frame of the reconstructed top quark
$\Delta p_{\mathrm{T}}(\ell\nu b, j)$	Δp_{T} of the reconstructed top quark and the untagged jet
$\Delta R(\ell, j)$	ΔR of the charged lepton and the untagged jet

t-channel 13 TeV: fit and analysis

Binned maximum likelihood fit performed in l^+ and l^- signal regions

Pseudo-experiments varying signal acceptance, BG rates, and signal shape of NN distribution are used to estimate systematic unc.

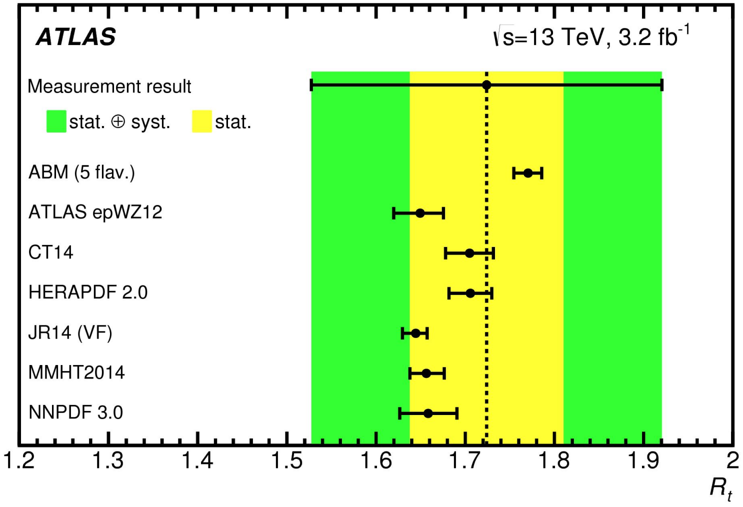
Process	$\hat{\beta}$	$\hat{\nu}(\ell^+)$	$\hat{\nu}(\ell^-)$
tq	1.15 ± 0.03	4840 ± 140	–
$\bar{t}q$	1.12 ± 0.05	–	3040 ± 130
$t\bar{t}, Wt, t\bar{b} + \bar{t}b$	0.91 ± 0.03	$13\,700 \pm 510$	$13\,600 \pm 510$
W^++ jets	1.13 ± 0.05	$12\,000 \pm 550$	–
W^-+ jets	1.21 ± 0.06	–	$10\,500 \pm 550$
Z, VV+ jets	–	1530	1410
Multijet background	–	2420	2420
Total estimated	–	$34\,500 \pm 760$	$31\,000 \pm 760$
Total observed	–	34 459	31 056

Source	$\frac{\Delta\sigma(tq)}{\sigma(tq)}$ [%]	$\frac{\Delta\sigma(\bar{t}q)}{\sigma(\bar{t}q)}$ [%]	$\frac{\Delta R_t}{R_t}$ [%]
Data statistics	± 2.9	± 4.1	± 5.0
Monte Carlo statistics	± 2.8	± 4.2	± 5.1
Reconstruction efficiency and calibration uncertainties			
Muon uncertainties	± 0.8	± 0.9	± 1.0
Electron uncertainties	< 0.5	± 0.5	± 0.7
JES	± 3.4	± 4.1	± 1.2
Jet energy resolution	± 3.9	± 3.1	± 1.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	± 0.9	± 1.2	< 0.5
b-tagging efficiency	± 7.0	± 6.9	< 0.5
c-tagging efficiency	< 0.5	± 0.5	± 0.6
Light-jet tagging efficiency	< 0.5	< 0.5	< 0.5
Pile-up reweighting	± 1.5	± 2.2	± 3.8
Monte Carlo generators			
tq parton shower generator	± 13.0	± 14.3	± 1.9
tq NLO matching	± 2.1	± 0.7	± 2.8
tq radiation	± 3.7	± 3.4	± 3.7
$t\bar{t}$, Wt, $t\bar{b} + \bar{t}b$ parton shower generator	± 3.2	± 4.4	± 1.2
$t\bar{t}$, Wt, $t\bar{b} + \bar{t}b$ NLO matching	± 4.4	± 8.6	± 4.6
$t\bar{t}$, Wt, $tb + \bar{t}b$ radiation	< 0.5	± 1.1	± 0.7
PDF	± 0.6	± 0.9	< 0.5
Background normalisation			
Multijet normalisation	± 0.3	± 2.0	± 1.8
Other background normalisation	± 0.4	± 0.5	< 0.5
Luminosity	± 2.1	± 2.1	< 0.5
Total systematic uncertainty	± 17.5	± 20.0	± 10.2
Total uncertainty	± 17.8	± 20.4	± 11.4

t-channel 13 TeV: results

Top and anti-top cross-sections measured independently, as well as their ratio R_t:

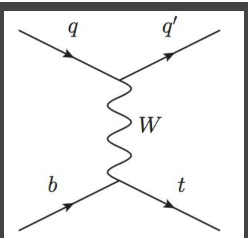
$$\sigma(tq) = 156 \pm 5\,(\text{stat.}) \pm 27\,(\text{syst.}) \pm 3\,(\text{lumi.})\ \text{pb}$$
$$\sigma(\bar{t}q) = 91 \pm 4\,(\text{stat.}) \pm 18\,(\text{syst.}) \pm 2\,(\text{lumi.})\ \text{pb}$$
$$R_t = 1.72 \pm 0.09\,(\text{stat.}) \pm 0.18(\text{syst.}),$$



Ratio measurements compared to predictions from several PDF models (right)

Measurements are all in agreement with best SM predictions

t-channel 8 TeV cross-sections

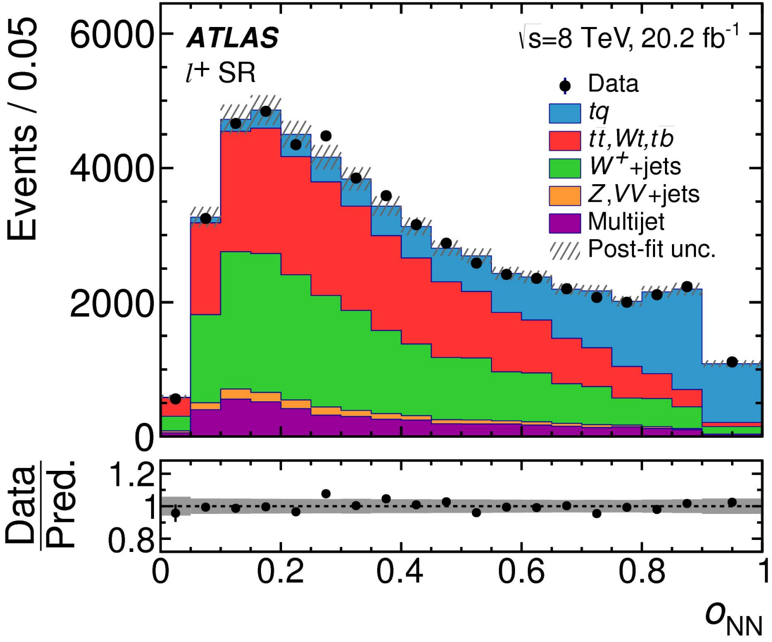


Submitted to EPJC
20.2 fb^{-1}
2012
$\sqrt{s}$=8 TeV

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

Variety of tests of **NLO calculations**, measurements of $\boldsymbol{V_{tb}}$ **vertex**, test of **PDF models**

Similar techniques as 13 TeV, following slides will focus on results/interpretation



t-channel 8 TeV: uncertainties

Uncertainties on fiducial cross-sections are more **evenly spread** among sources than in the 13 TeV measurement

Dominant uncertainties are **lepton reco**, **JES**, background **top pair 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
$E_{\text{T}}^{\text{miss}}$ 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

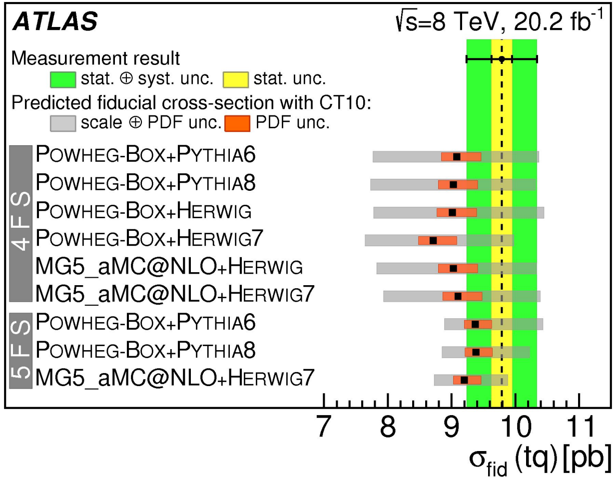
t-channel 8 TeV: fiducial/inclusive

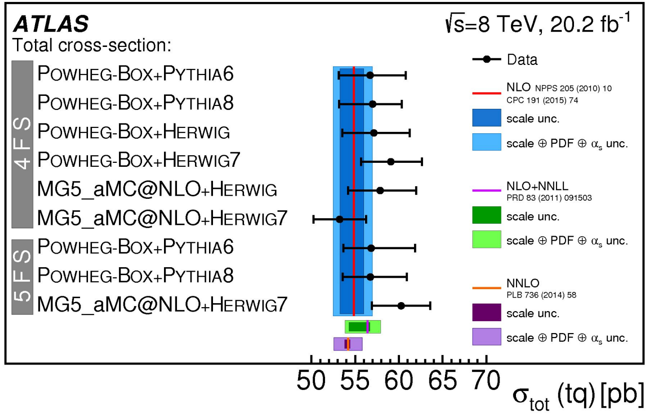
Fiducial cross-section (top) measured only in region of interest defined by particle observables

Fiducial region defined to be close to reconstructed event acceptance:

1 charged lepton, 2 jets (1 b-tagged), m(*lb*)>160 GeV

Total cross-section (below) extrapolated to full phase-space, comparable with fixed-order calculations

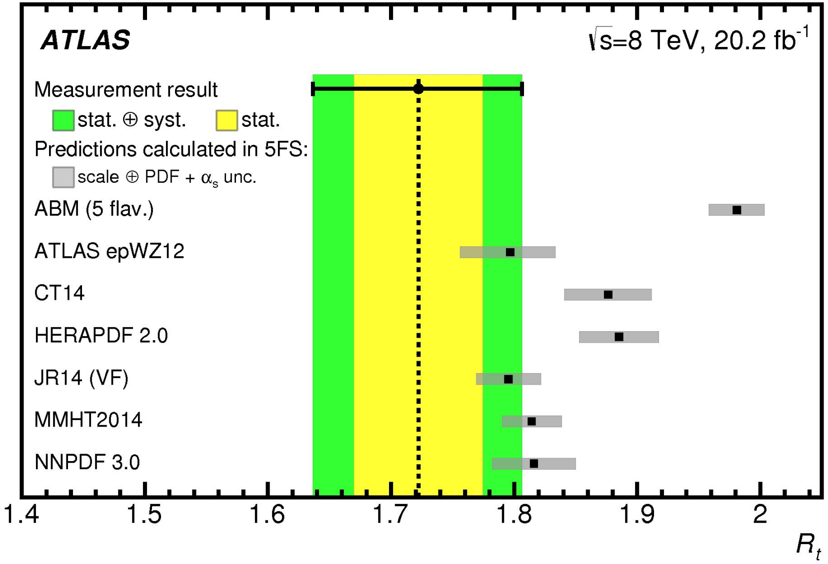




t-channel ratio measurement

Ratio of top to anti-top cancels many uncertainties, discriminates between PDF predictions

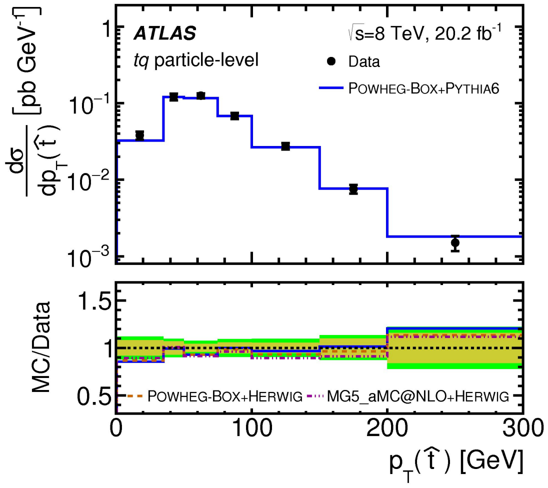
Uncertainties on R_t dominated by **statistics**, **top pair MC** model

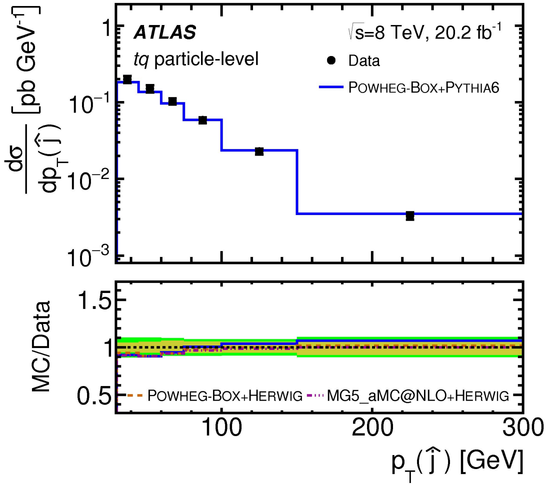


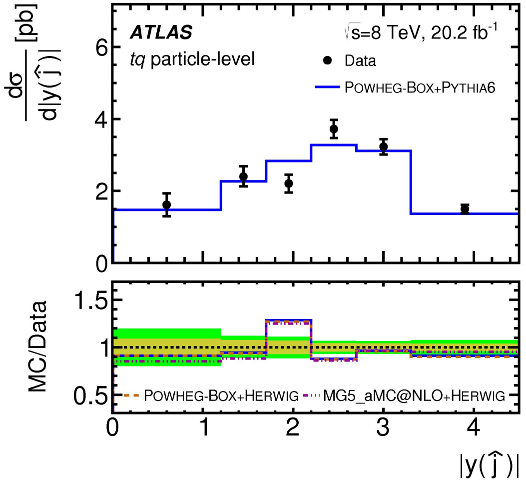
Source	$\Delta R_t/R_t$ [%]
Data statistics	± 3.0
Monte Carlo statistics	± 1.8
Background modelling	± 0.7
Jet reconstruction	± 0.5
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	± 0.6
tq ($\bar{t}q$) NLO matching	± 0.5
tq ($\bar{t}q$) scale variations	± 0.7
$t\bar{t}$ NLO matching	± 2.3
$t\bar{t}$ parton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

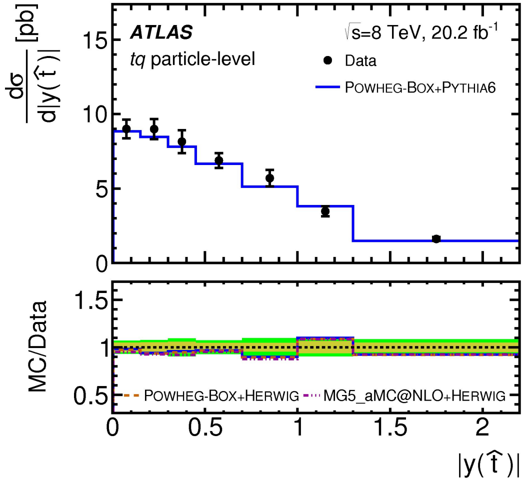
t-channel cross-sections

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



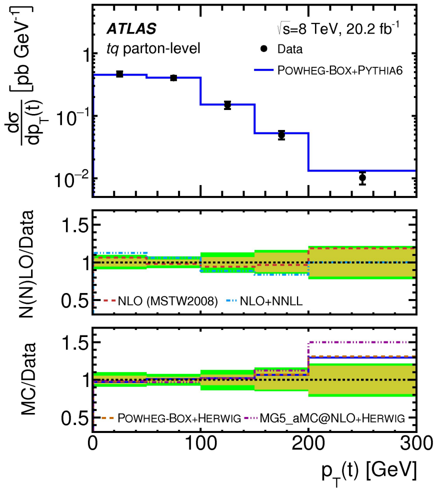


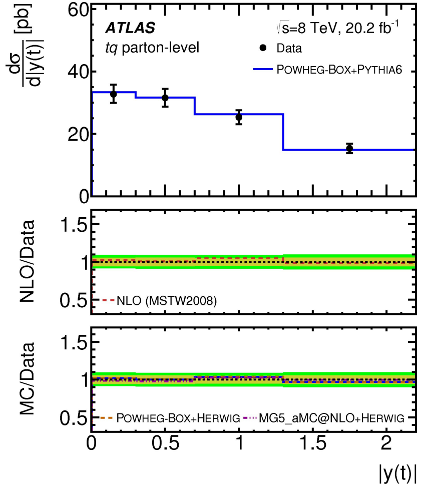


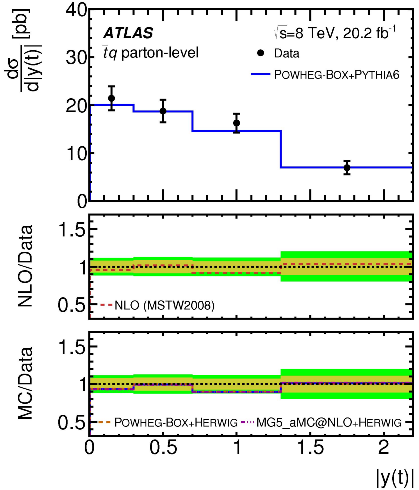


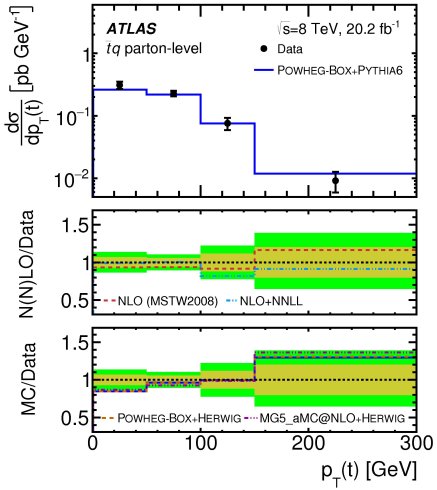
t-channel cross-sections

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









Wt 13 TeV cross-section

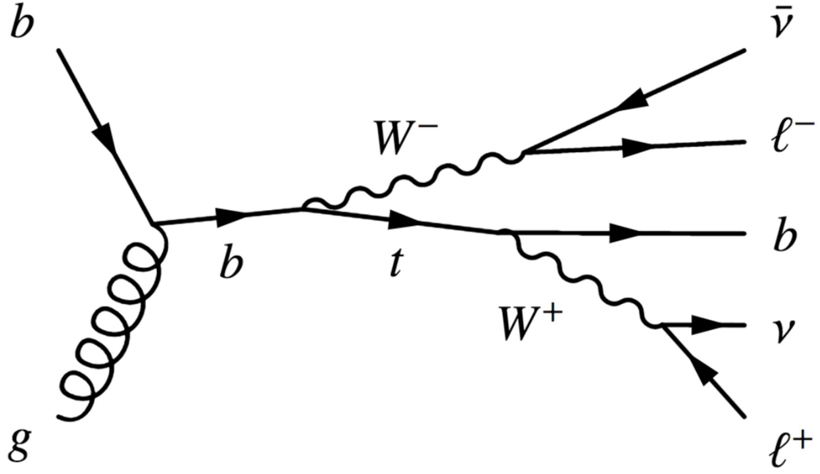
Submitted to JHEP
3.2 fb^{-1}
2015
$\sqrt{s}$=13 TeV

First 5σ observation of this process was in 8 TeV LHC data by ATLAS and CMS

Primary goal now is to explore *Wtb* vertex in a new kinematic regime (13 TeV)

Theoretical cross-section (NLO+NNLL):

σ_{theory} = 71.7 ± 1.8 (scale) ± 3.4 (PDF) pb

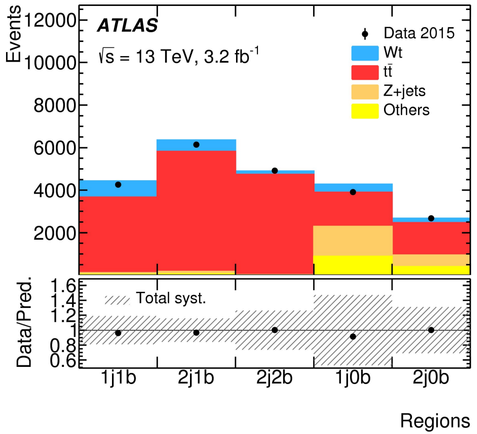


Wt 13 TeV: event selection

Require two charged leptons and at least 1 jet

Separate based on number of jets (j) and *b*-tagged jets (b): 1j1b, 2j1b, 2j2b

Various E_T^{miss} and m_{ll} cuts to reduce Z+jets background



At least one jet with $p_T > 25\,\text{GeV}$, $\lvert\eta\rvert < 2.5$		
Exactly two leptons of opposite charge with $p_T > 20\,\text{GeV}$, $\lvert\eta\rvert < 2.5$ for muons and $\lvert\eta\rvert < 2.47$ excluding $1.37 < \lvert\eta\rvert < 1.52$ for electrons		
At least one lepton with $p_T > 25\,\text{GeV}$, veto if third lepton with $p_T > 20\,\text{GeV}$		
At least one lepton matched to the trigger object		
Different flavour	$E_T^{miss} > 50\,\text{GeV}$,	if $m_{\ell\ell} < 80\,\text{GeV}$
	$E_T^{miss} > 20\,\text{GeV}$,	if $m_{\ell\ell} > 80\,\text{GeV}$
Same flavour	$E_T^{miss} > 40\,\text{GeV}$,	always
	veto,	if $m_{\ell\ell} < 40\,\text{GeV}$
	$4E_T^{miss} > 5m_{\ell\ell}$,	if $40\,\text{GeV} < m_{\ell\ell} < 81\,\text{GeV}$
	veto,	if $81\,\text{GeV} < m_{\ell\ell} < 101\,\text{GeV}$
	$2m_{\ell\ell} + E_T^{miss} > 300\,\text{GeV}$,	if $m_{\ell\ell} > 101\,\text{GeV}$

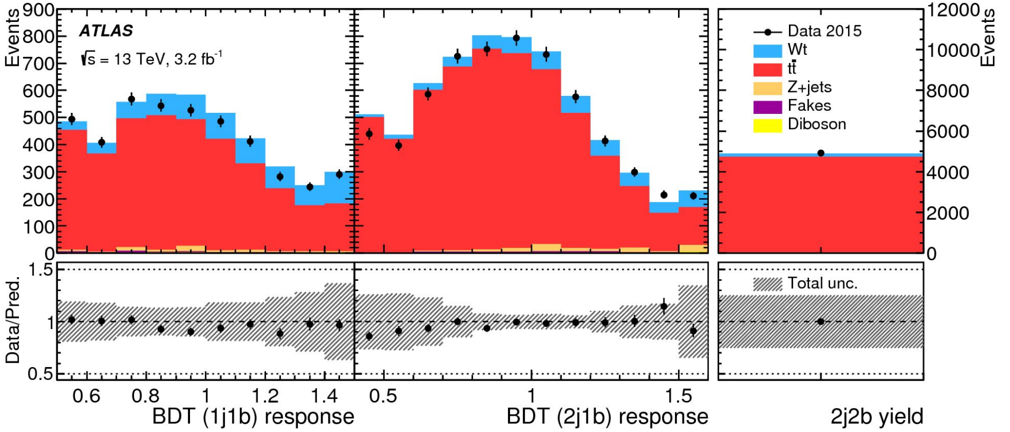
Wt 13 TeV: BDT analysis

Boosted decision tree trained for 1j1b and 2j1b regions

Inputs based on momenta, angles of leptons, jets, E_T^{miss}

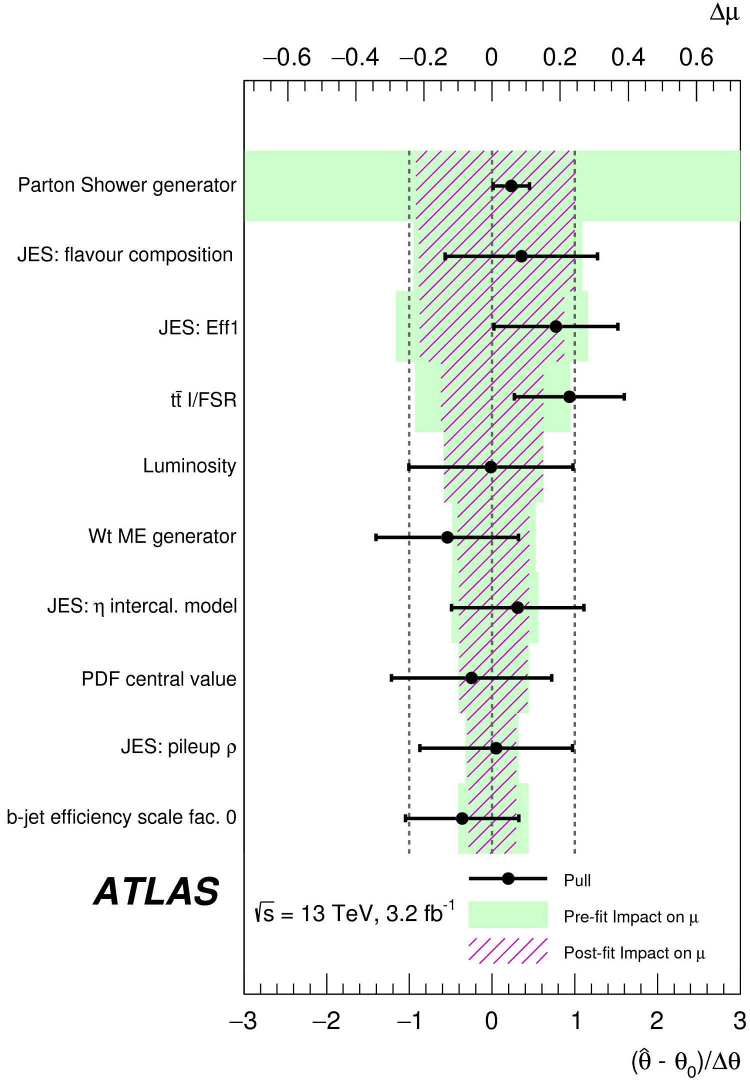
1j1b	
Variable	S $[10^{-2}]$
$p_T^{sys}(\ell_1\ell_2 E_T^{miss} j_1)$	5.3
$\Delta p_T(\ell_1\ell_2, E_T^{miss} j_1)$	2.9
$\sum E_T$	2.7
$\Delta p_T(\ell_1\ell_2, E_T^{miss})$	1.2
$p_T^{sys}(\ell_1 E_T^{miss} j_1)$	0.9
$C(\ell_1\ell_2)$	0.9
$\Delta p_T(\ell_1, E_T^{miss})$	0.8
BDT discriminant	8.6

2j1b	
Variable	S $[10^{-2}]$
$p_T^{sys}(\ell_1\ell_2)$	1.7
$\Delta R(\ell_1\ell_2, E_T^{miss} j_1 j_2)$	1.7
$\Delta R(\ell_1\ell_2, j_1 j_2)$	1.5
$m(\ell_1 j_2)$	1.4
$\Delta p_T(\ell_1\ell_2, E_T^{miss})$	1.4
$\Delta p_T(\ell_1, j_1)$	1.4
$m(\ell_1 j_1)$	1.3
$p_T(\ell_1)$	1.3
$\sigma(p_T^{sys})(\ell_1\ell_2 E_T^{miss} j_1)$	1.2
$\Delta R(\ell_1, j_1)$	1.2
$p_T(j_2)$	0.9
$\sigma(p_T^{sys})(\ell_1\ell_2 E_T^{miss} j_1 j_2)$	0.9
$m(\ell_2 j_1 j_2)$	0.3
$m(\ell_2 j_1)$	0.3
$m(\ell_2 j_2)$	0.1
BDT discriminant	10.9



Wt 13 TeV: Fitting

- Binned maximum **likelihood fit** to BDT distribution in 1j1b, 2j1b, and total yield in 2j2b
- Top pair-enriched bins act as **control regions** to **constrain** parton shower, initial/final state radiation systematics
- Most significant systematics are **top pair model**, **jet energy scale**



Wt 13 TeV: Fitting

Binned maximum **likelihood fit** to BDT distribution in 1j1b, 2j1b, and total yield in 2j2b

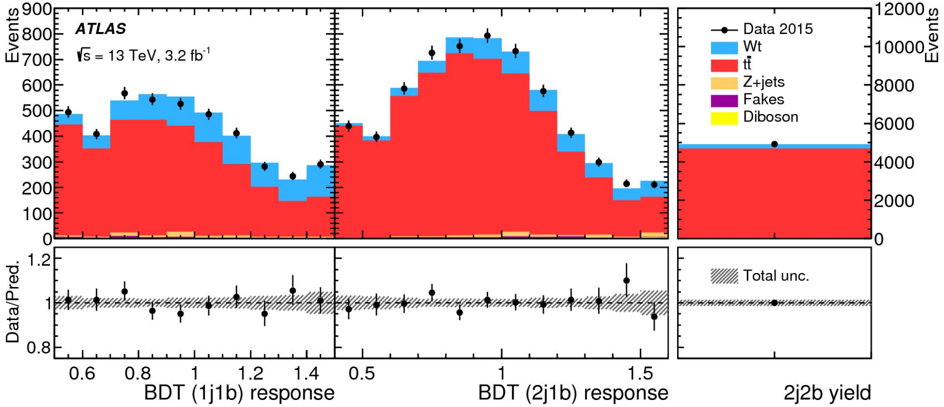
Top pair-enriched bins act as **control regions** to **constrain** parton shower, initial/final state radiation systematics

Most significant systematics are **top pair model**, **jet energy scale**

Source	$\Delta\sigma_{Wt}/\sigma_{Wt}$[%]
Jet energy scale	21
Jet energy resolution	8.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft terms	5.3
b-tagging	4.3
Luminosity	2.3
Lepton efficiency, energy scale and resolution	1.3
NLO matrix element generator	18
Parton shower and hadronisation	7.1
Initial-/final-state radiation	6.4
Diagram removal/subtraction	5.3
Parton distribution function	2.7
Non-$t\bar{t}$ background normalisation	3.7
Total systematic uncertainty	30
Data statistics	10
Total uncertainty	31

Wt 13 TeV: results

- Measured cross-section agrees well with NLO+NNLL prediction
- Post-fit BDT distributions also show good agreement with MC predictions

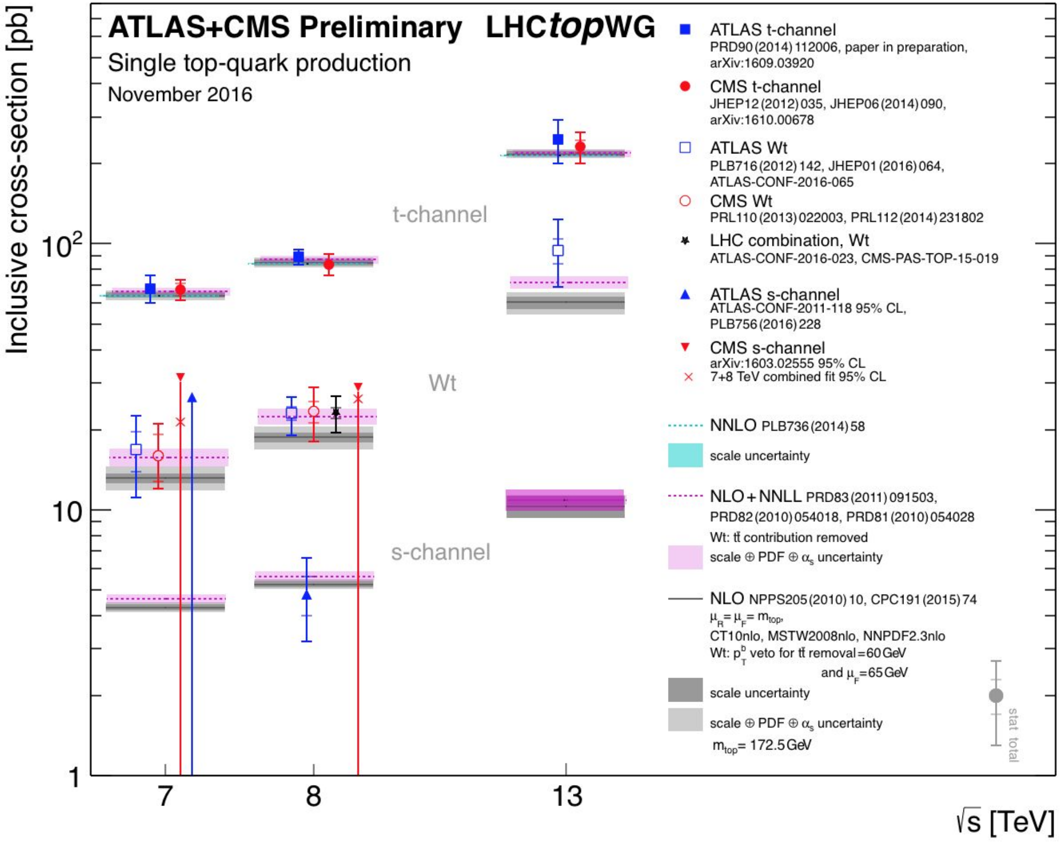


$$\sigma_{Wt} = 94 \pm 10\ (\text{stat.})\ {}^{+28}_{-22}\ (\text{syst.}) \pm 2\ (\text{lumi.})\ \text{pb}$$

Summary

Top quark physics in ATLAS has been an extremely productive area in 2016-2017

Many new results still to come with Run 2 data!



Backup slides