Single Top-quark production cross-section measurements using the ATLAS detector at the LHC

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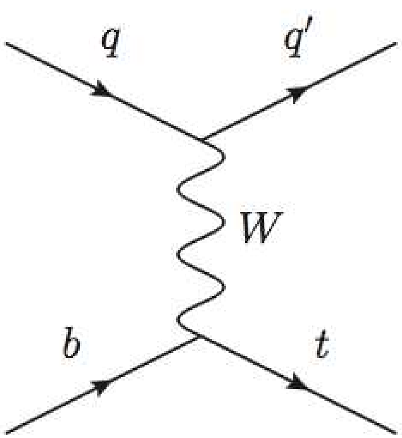
on behalf of the ATLAS Collaboration

Single top-quark production.

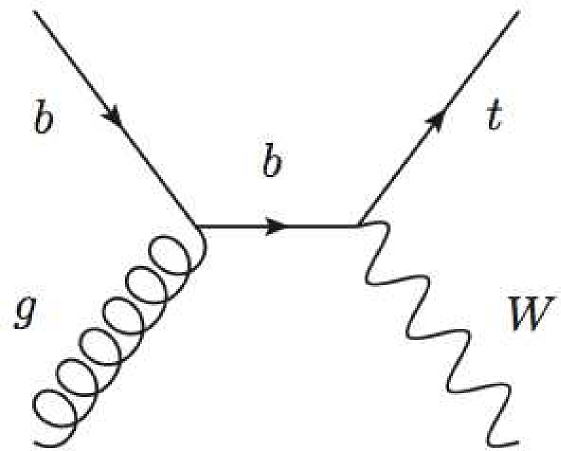
- **Top-quark properties.**
  - Heaviest particle in the SM.
  - Direct access to bare quark properties.
  - Top-quark decays almost exclusively to $t \to Wb$.

- **Why (single) top-quark production is important?**
  - Test of SM:
    - Can constrain PDFs.
    - Test CKM matrix unitarity.
    - Test pQCD calculations.
  - Probe BSM physics:
    - Anomalous couplings with Wtb vertex.

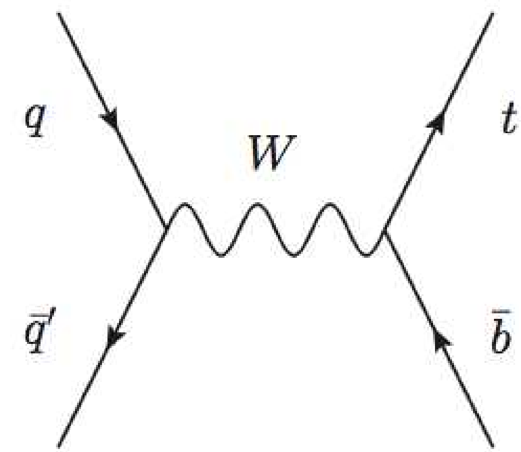
t-channel



tW-channel



s-channel



$$\sigma(8\ \text{TeV}) = 87.7^{+3.4}_{-1.9}\text{pb}$$
$$\sigma(13\ \text{TeV}) = 217.0^{+9.1}_{-7.7}\text{pb}$$

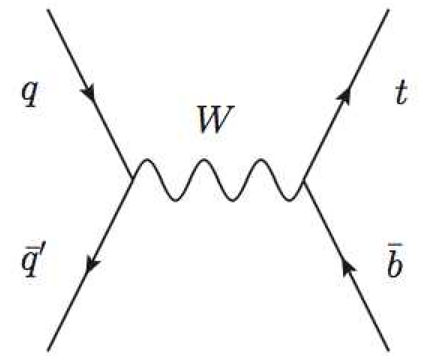
$$\sigma(8\ \text{TeV}) = 22.4 \pm 1.5\text{pb}$$
$$\sigma(13\ \text{TeV}) = 71.7 \pm 3.8\text{pb}$$

$$\sigma(8\ \text{TeV}) = 5.6 \pm 0.2\text{pb}$$
$$\sigma(13\ \text{TeV}) = 10.3 \pm 0.4\text{pb}$$

s-channel @ 8TeV: total measurement.

PLB 756 (2016), 228-246

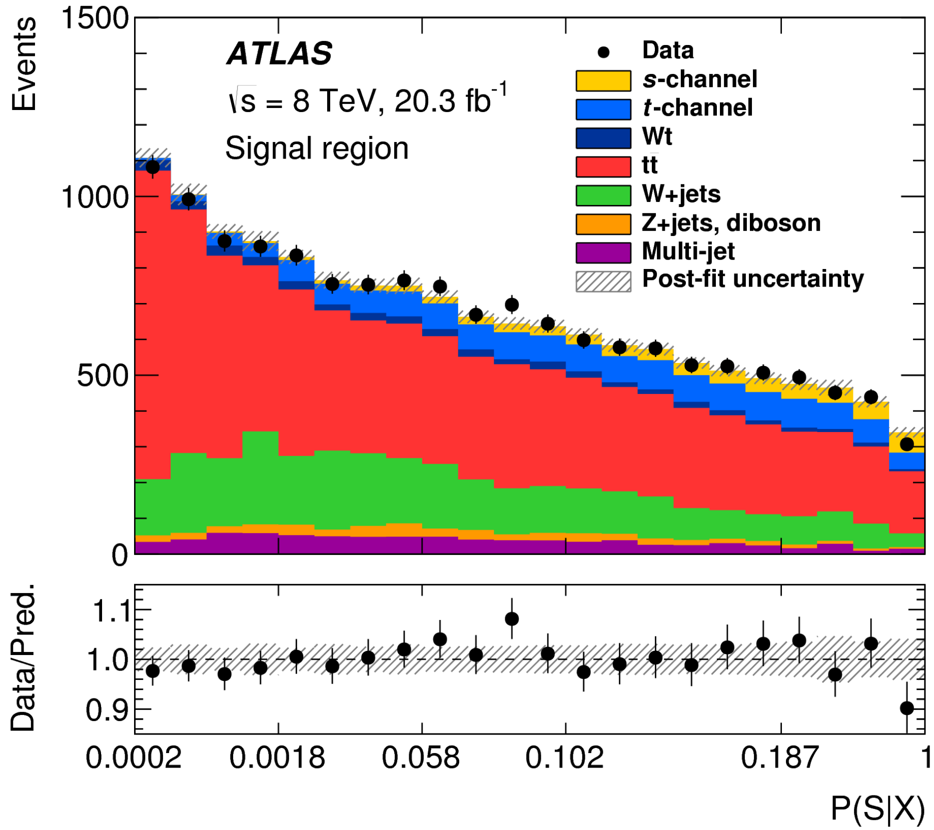
- **Signal signature (leptonic decay of W boson).**
  - 1 isolated lepton.
  - E_T^{MISS} from the neutrino.
  - 2 high P_T *b*-tagged jets.
- **Main backgrounds:**
  - **ttbar** (dilepton veto to reduce it), **W+jets**.
- **Matrix Element method to separate tb signal from backgrounds.**



8 TeV	1j	2j	3j	4j
0b				
1b				
1b(loose)		CR (W+jets)		
2b		SR		VR (ttbar)

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

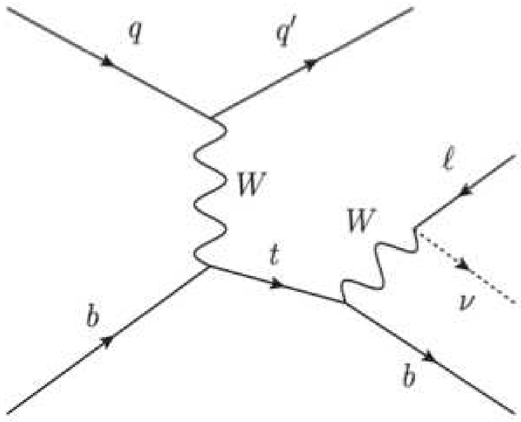
observed (expected) significance : 3.2 σ (3.9 σ)



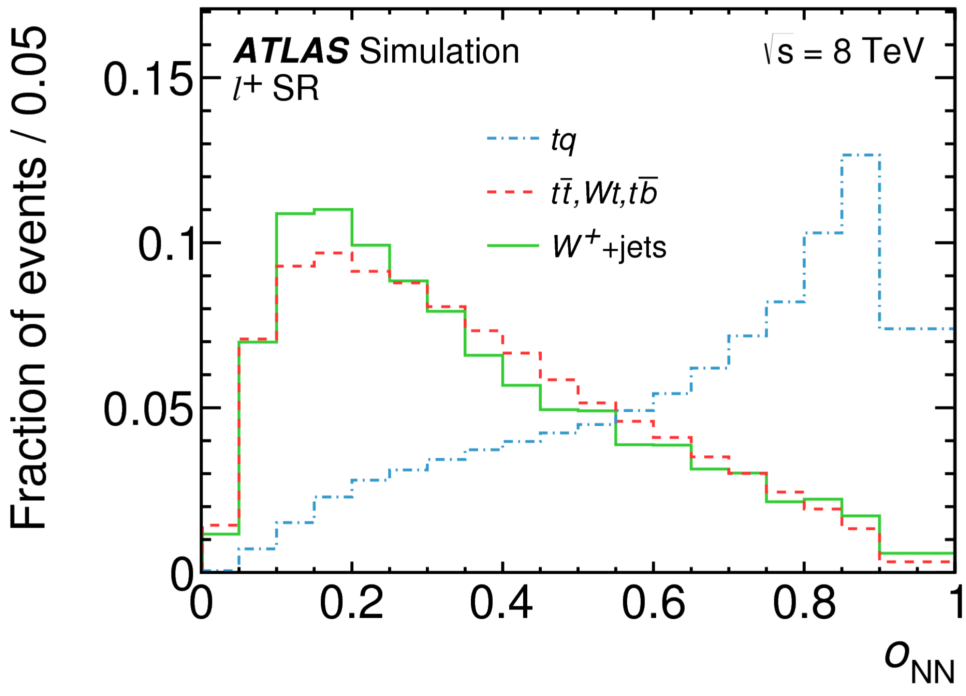
- **Binned likelihood fit to extract the cross section in signal region. W+jets CR used in the fit.**

8 TeV: Eur. Phys. J. C 77 (2017) 531 13 TeV: JHEP04(2017)086

- **Separate measurements of σ(tq) and σ($\bar{t}$q).**
- **Signal signature (leptonic decay of W boson).**
  - 1 isolated lepton.
  - E_T^{MISS} from the neutrino
  - High P_T forward (spectator) jet.
  - High P_T b-tagged jet.
- **Main backgrounds:**
  - ttbar, W+jets.
  - E_T^{MISS} used to supress multijet contributions

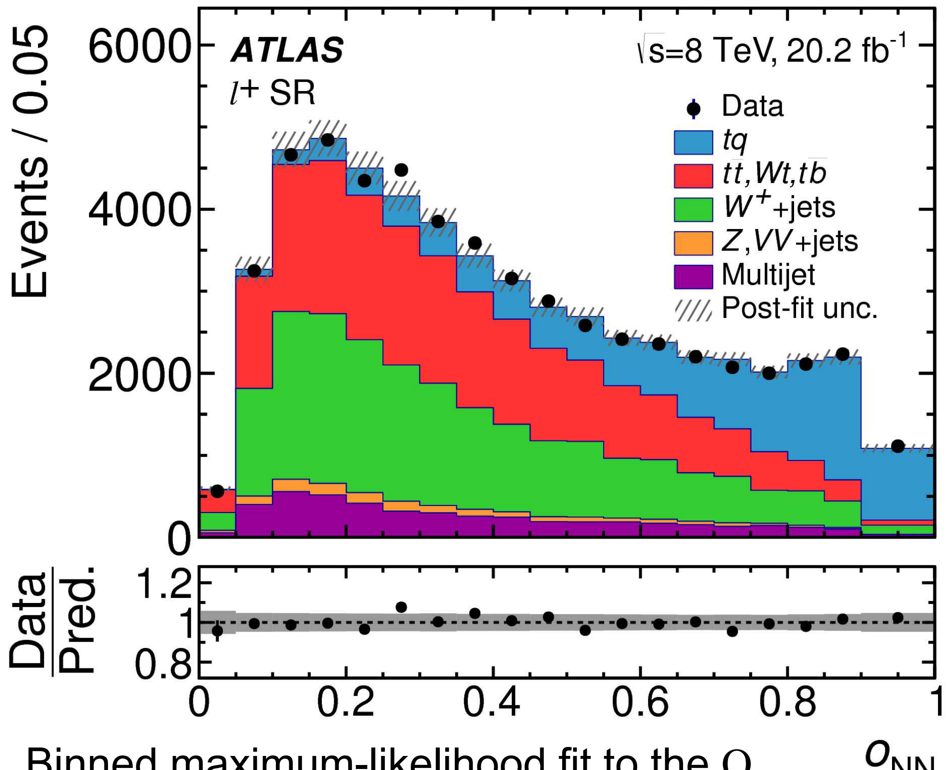


Neural network to separate signal and background.



8 TeV / 13 TeV	1j	2j	3j
0b			
1b(loose)		VR (W+jets)	
1b		SR (1^+) SR (1^-)	
2b		VR (ttbar)	

- **Fiducial phase space measurement.**
  - Reduces systematic uncertainties related with MC generators.
  - Region defined by stables particles with selection close to reconstructed objects.
- **Neural network (NN):**
  - 7 input variables combined into the NN discriminant.
  - Improves sensitivity of the signal extraction.



  - Binned maximum-likelihood fit to the O_{NN}.

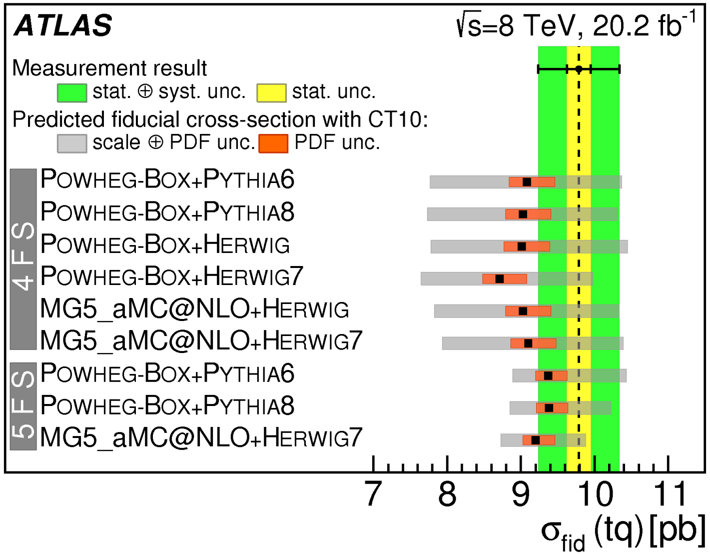
- **Fiducial phase space volume.**

$$\sigma_{\text{fid}} = \frac{N_{\text{fid}}}{N_{\text{sel}}} \cdot \frac{\hat{\nu}}{L_{\text{int}}}$$

Main systematics:

- jet energy scale (2.5%)
- NLO matching (4.6 %)
- lepton reconstruction (2.5 %).

$$\sigma_{\text{fid}}(tq) = 9.78 \pm 0.57 \text{ pb}$$
$$\sigma_{\text{fid}}(\bar{t}q) = 5.77 \pm 0.45 \text{ pb}$$



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JHEP04(2017)086

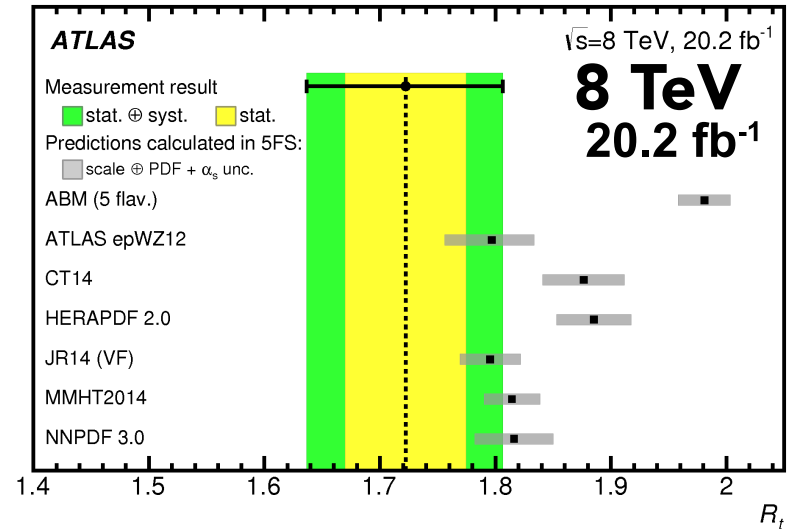
8 TeV

$\sigma_{tot}(\bar{t}q) = 32.9^{+3.0}_{-2.7}\,\text{pb}\,(9.1\%)$

$\sigma_{tot}(tq) = 56.7^{+4.3}_{-3.8}\,\text{pb}\,(7.6\%)$

$|f_{LV} \cdot V_{tb}| = 1.029 \pm 0.048\,(4.6\%)$

$R_t = 1.72 \pm 0.09\,(4.9\%)$



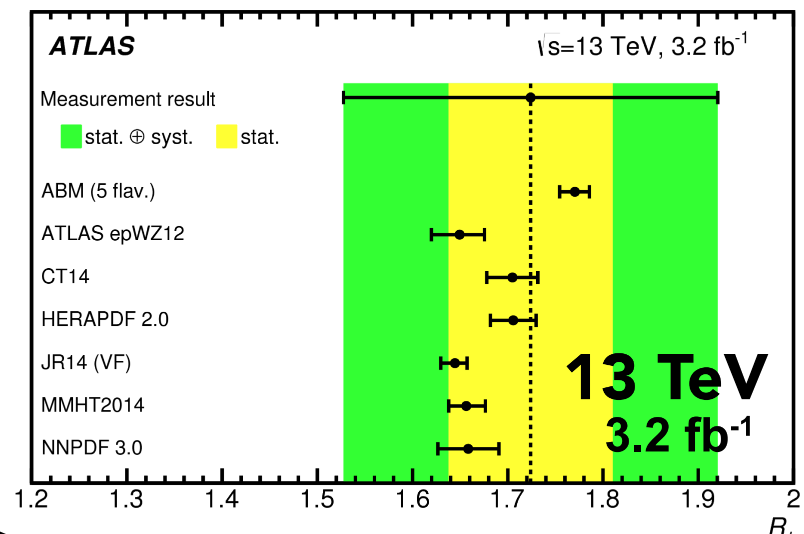
- **Extrapolation to total phase space.**

$$\sigma_{tot} = \frac{1}{A_{fid}} \cdot \sigma_{fid}$$

$$R_t = \sigma_{tot}(tq)/\sigma_{tot}(\bar{t}q)$$

- **$|V_{tb}|$ without assuming unitarity from the inclusive cross section $\sigma(tq+\bar{t}q)$.**

$$|f_{LV} \cdot V_{tb}|^2 = \sigma_{meas}/\sigma_{SM}$$



13 TeV

$\sigma_{tot}(\bar{t}q) = 91 \pm 19\,\text{pb}\,(20.4\%)$

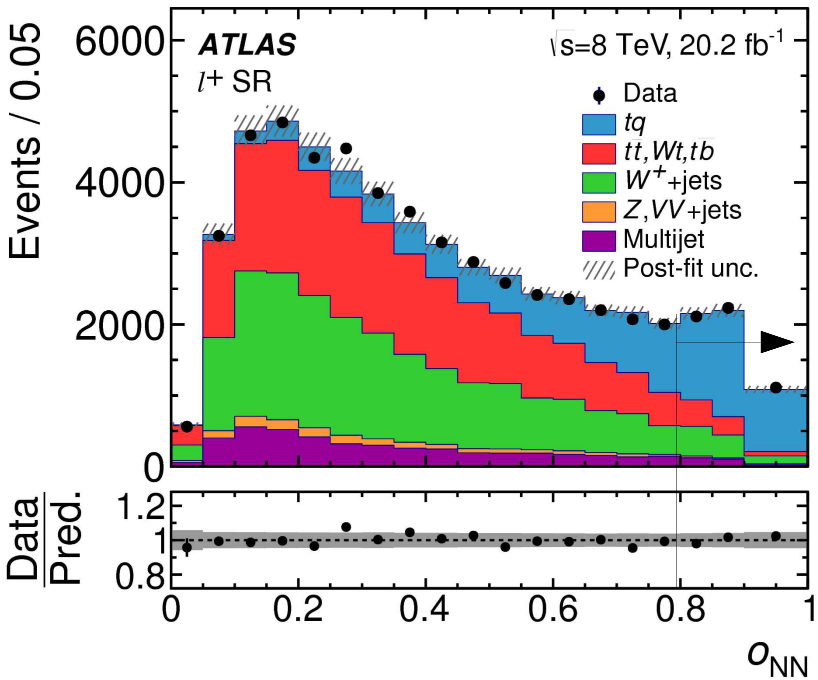
$\sigma_{tot}(tq) = 156 \pm 28\,\text{pb}\,(17.8\ \%)$

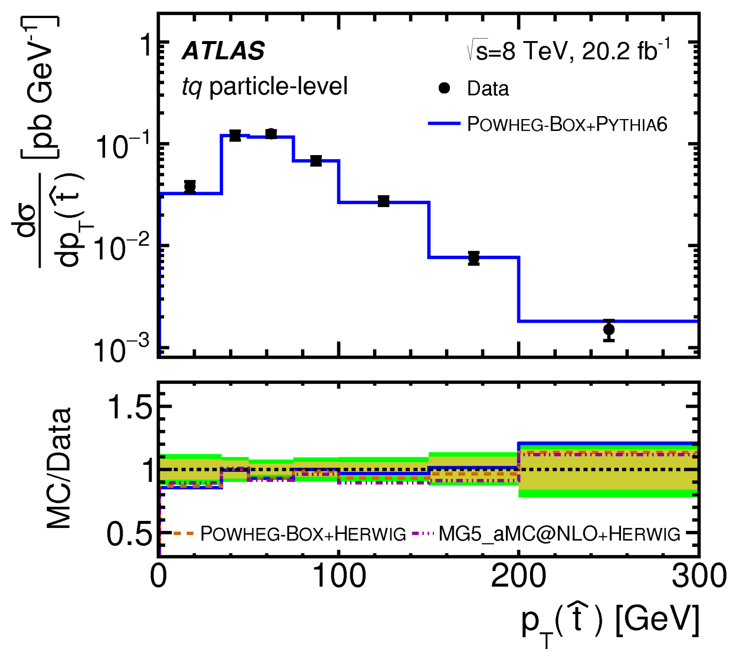
$|f_{LV} \cdot V_{tb}| = 1.07 \pm 0.09\,(8.4\%)$

$R_t = 1.72 \pm 0.20\,(11.4\%)$

dominant syst: MC generators (tq parton shower)

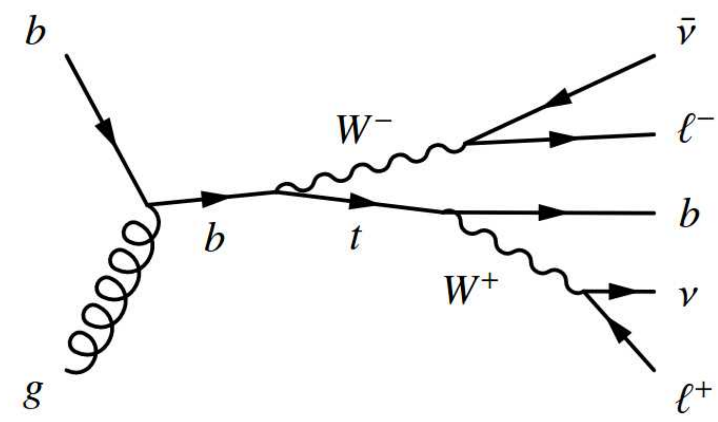
- **Differential measurement.**
  - **Cut** in Neural Network output to **enhance signal-background ratio.** $O_{NN}>0.8$.
  - A different NN for the |y(t)| measurement to reduce distortion of the distribution.
  - Unfolded distributions at particle level.
    - P_T(t),P_T(jet) in two SR's (top and antitop).
    - |y(t)|, |y(jet)| in two SR's (top and antitop).
  - Unfolded distributions at parton level.
    - P_T(t) in two SR's (top and antitop).
    - |y(t)| in two SR's (top and antitop).



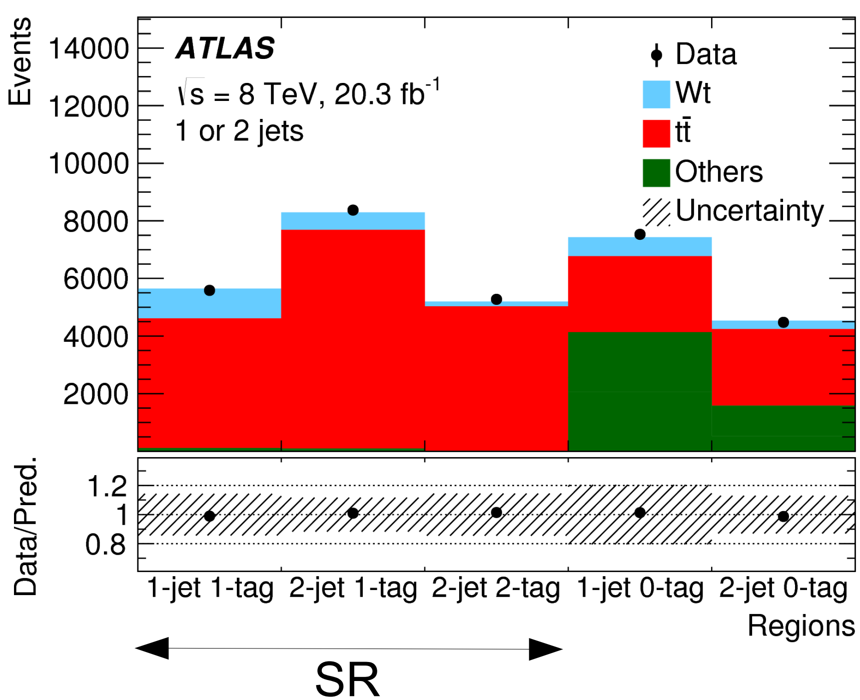


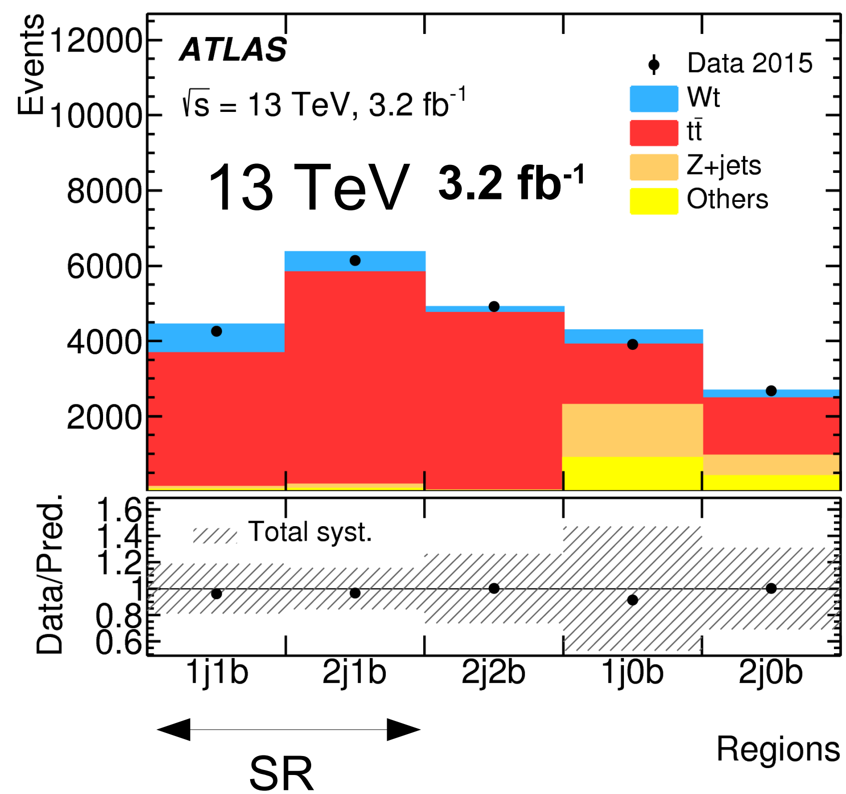
- **Background normalization:** theoretical predictions. Multijet determined w. data driven technique.
- **Main systematics:** jet enegy scale, modelling signal and ttbar.

- **Signal signature (leptonic decay of W boson).**
  - 2 isolated leptons (oppositely charged).
  - E_T^{MISS} from the two neutrinos.
  - High P_T b-tagged jet.
- **Main backgrounds:**
  - **ttbar** (interference at NLO).
  - E_T^{MISS} and dilepton invariant mass used to suppress **Z+jets** contributions.
- **Boosted Decision Tree** to separate **ttbar** from **tW.**



8 TeV
20.3 fb^{-1}





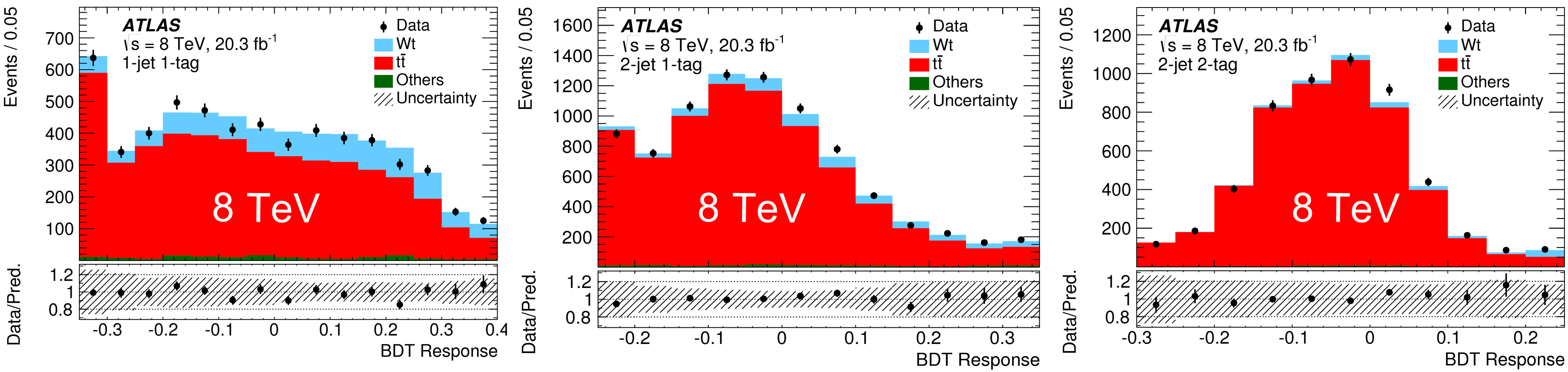
JHEP01(2016)064
JHEP 01 (2018) 63

8 TeV

- **3** separate **BDT's** trained to separate **tW** from **ttbar**.

13 TeV

- **2** separate **BDT's**. Same strategy than **8 TeV**.



Cross-section extracted from a **profile likelihood fit** to the **BDTs**. Two jet regions help to constrain **ttbar**

$$\sigma_{tot}(Wt) = 23.0 \pm 1.3\,(stat.)^{+3.2}_{-3.5}\,(syst.) \pm 1.1\,(lumi.)\,pb$$
$$(16\%)$$
$$|f_{LV} \cdot V_{tb}| = 1.01 \pm 0.10$$

$$\sigma_{tot}(Wt) = 94 \pm 10\,(stat.)^{+28}_{-22}\,(syst.) \pm 2\,(lumi.)\,pb$$
$$(31\%)$$

Main systematics:

- jet reconstruction (10%)
- initial/final state radiation (9.5%)
- ttbar normalisation (6%).

- **Main systematics:**
- jet energy scale (21%)
- NLO matrix element (18%).

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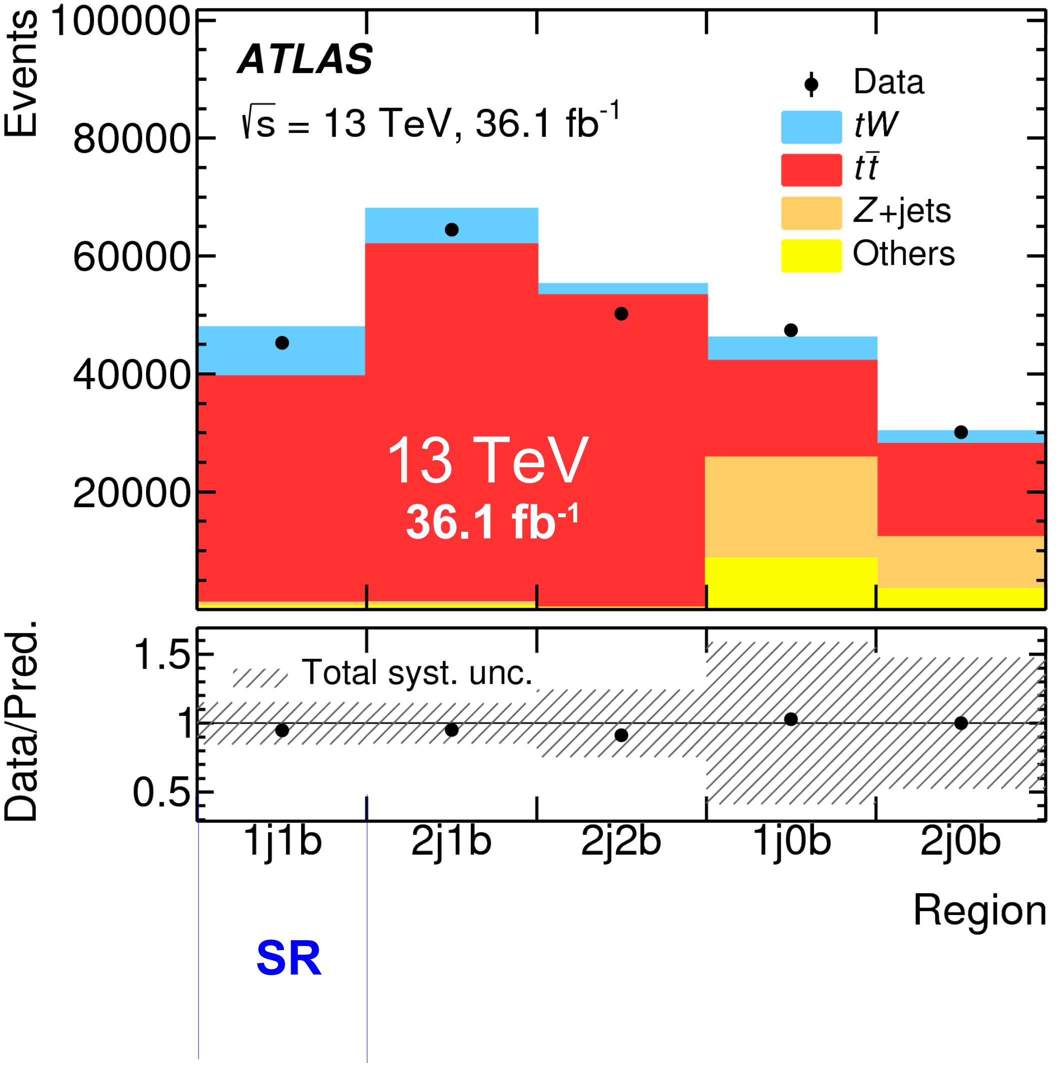
- **tW differential** analysis using **36.1 fb^{-1}** of 2015+2016 data.
- **Differential measurement:** fiducial phase space defined with two charged leptons and one b-jet.
- **Signal region**: exactly one b-jet, no additional jets.
  - **Validation regions** defined to validate the modelling. Not used in the cross-section measurement.
  - **Background subtraction:** theoretical predictions
  - To further suppress **ttbar** a **BDT** is used

Process	Events	Events BDT response > 0.3
tW	8 300 ± 1 400	1 970 ± 560
$t\bar{t}$	38 400 ± 6 600	3 400 ± 1 300
Z + jets	620 ± 310	159 ± 80
Diboson	230 ± 58	81 ± 20
Fakes	220 ± 220	19 ± 19
Predicted	47 800 ± 7 300	5 600 ± 1 700
Observed	45 273	5 043



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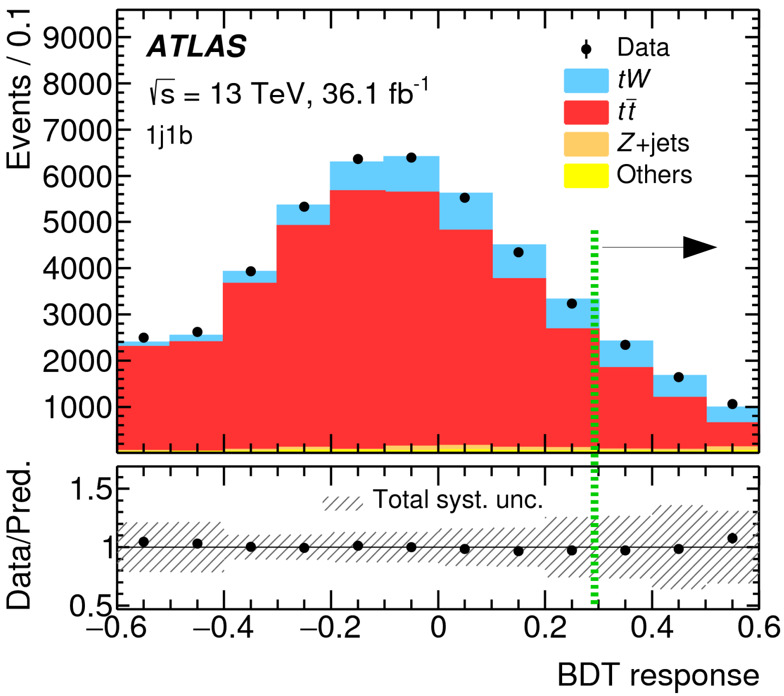
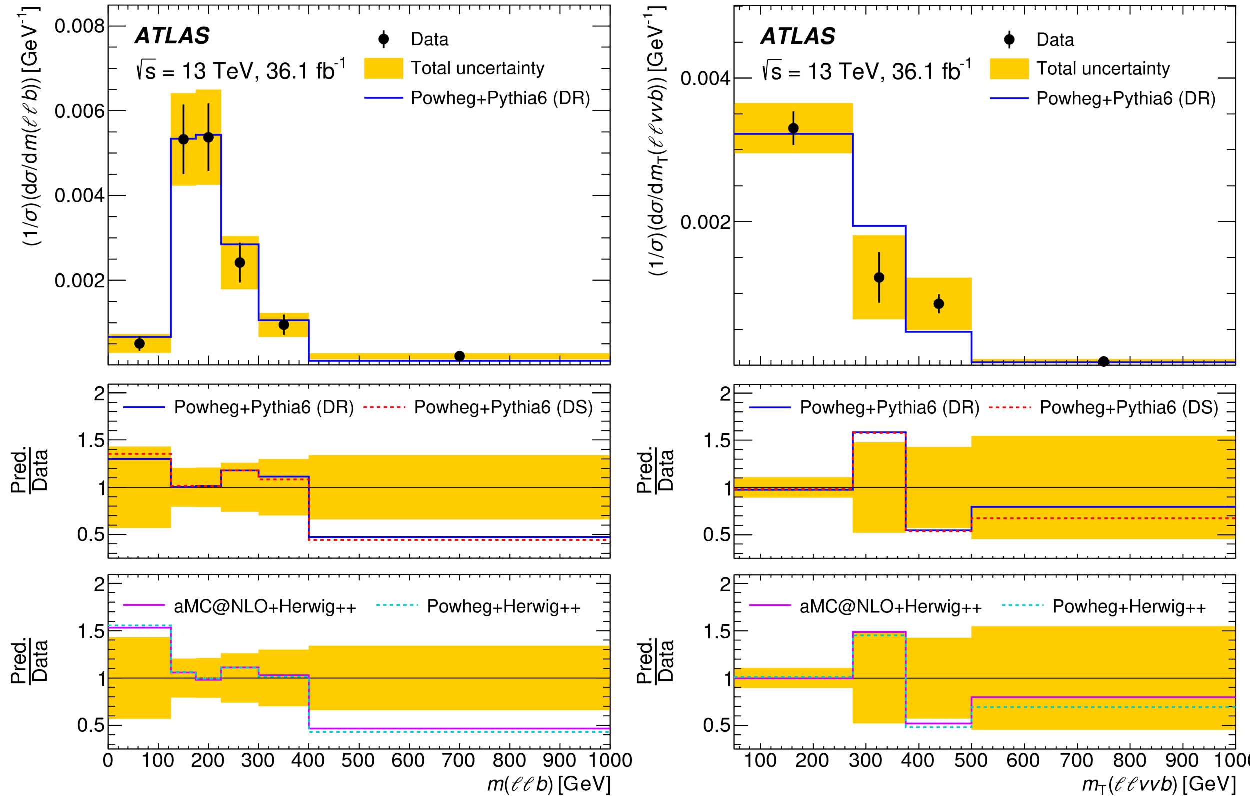




- **Unfolded distributions at particle level:**
- Differential cross-section extracted as function of several particle-level observables:
  - E(b) → top quark production.
  - $m(l_1b)$; $m(l_2b)$ → top quark decay.
  - E(llb); $\mathbf{m_T}$(llvvb); **m**(llb) → combined tW system.

Measurements are normalised wit the fiducial cross-section. Cancellation of main uncertainties.

Main uncetainties:

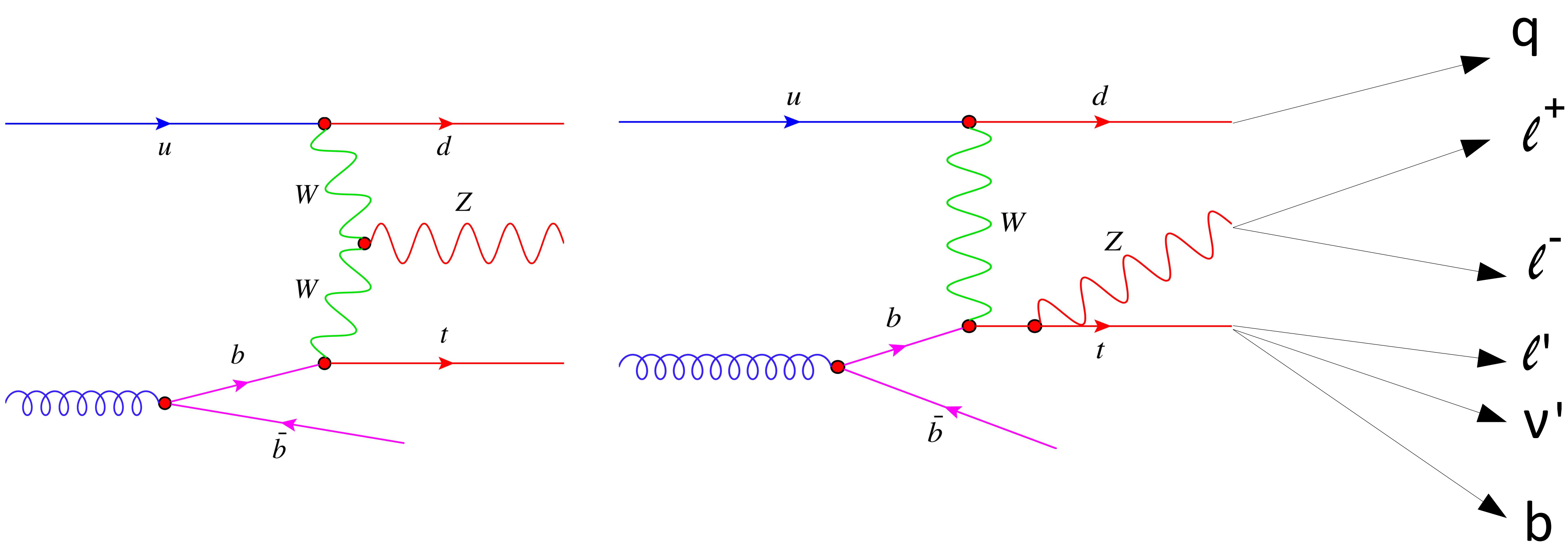
- Limited data statistics
- Signal modelling
- ttbar modelling.

tZq measurement @ 13 TeV.

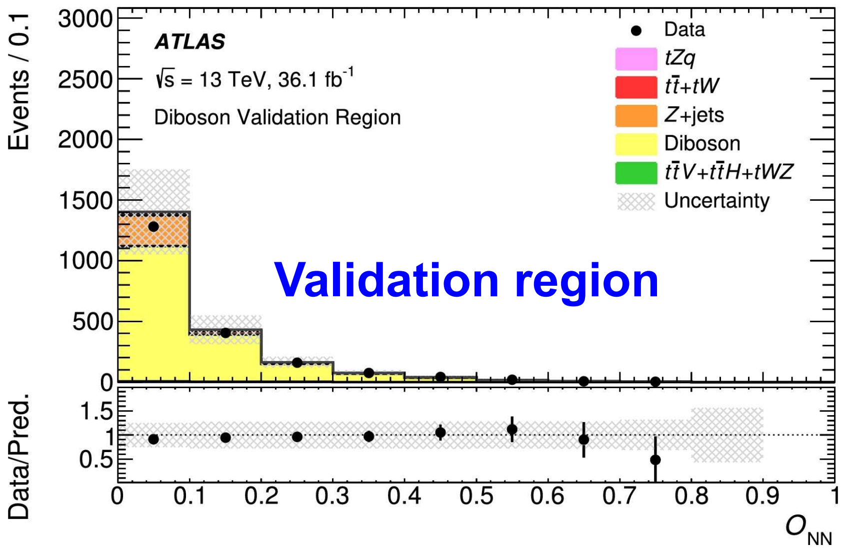
PLB 780 (2018), 557-577

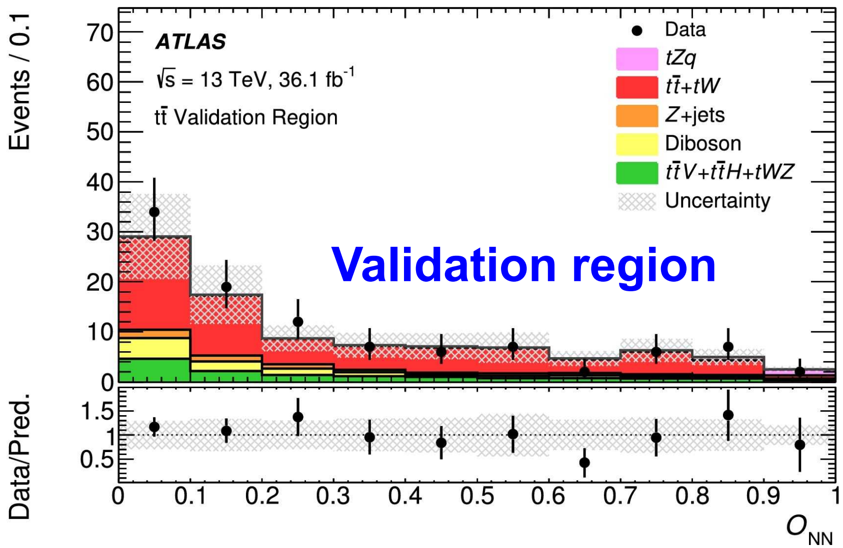
- **First evidence of SM tZq electroweak process.**.
  - Sensitive to tZ and WWZ coupling.
  - Important background to tH and tZ FCNC production.
- **Trilepton** decay channel is used. Signal signature:

  3 charged leptons, a *b*-jet and an additional non-*b*-jet.
- **Main backgrounds:**
  - **Diboson, ttbar**, **Z+jets**: Two **VR** and two **CR**
- **Background normalization:**
  - SF for **Diboson** from its control-region. Mostly WZ. ZZ with a non detected lepton is 9%
  - **ttbar** control region constrains non-promt leptons
  - **Z+jets** estimated w. data driven technique.



PLB 780 (2018), 557-577

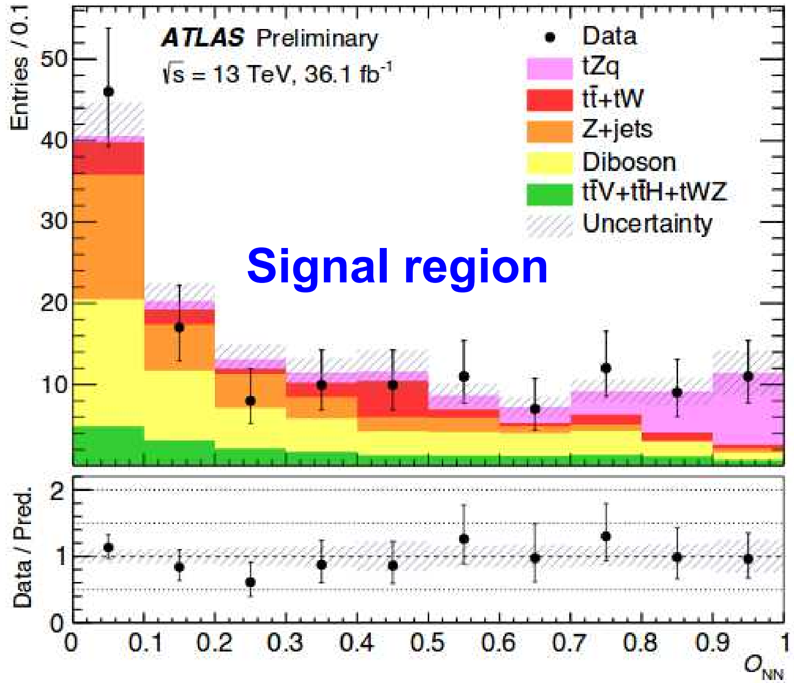




- **Neural network is used to enhace S/B.**
  - 10 variables used as input: η(j), P_T(j), m(t), …
- **Binned maximum likelihood fit to extract the cross section using the full NN discriminant distribution.**
- Impact of systematic uncertainties as nuisance parameters of the fit.

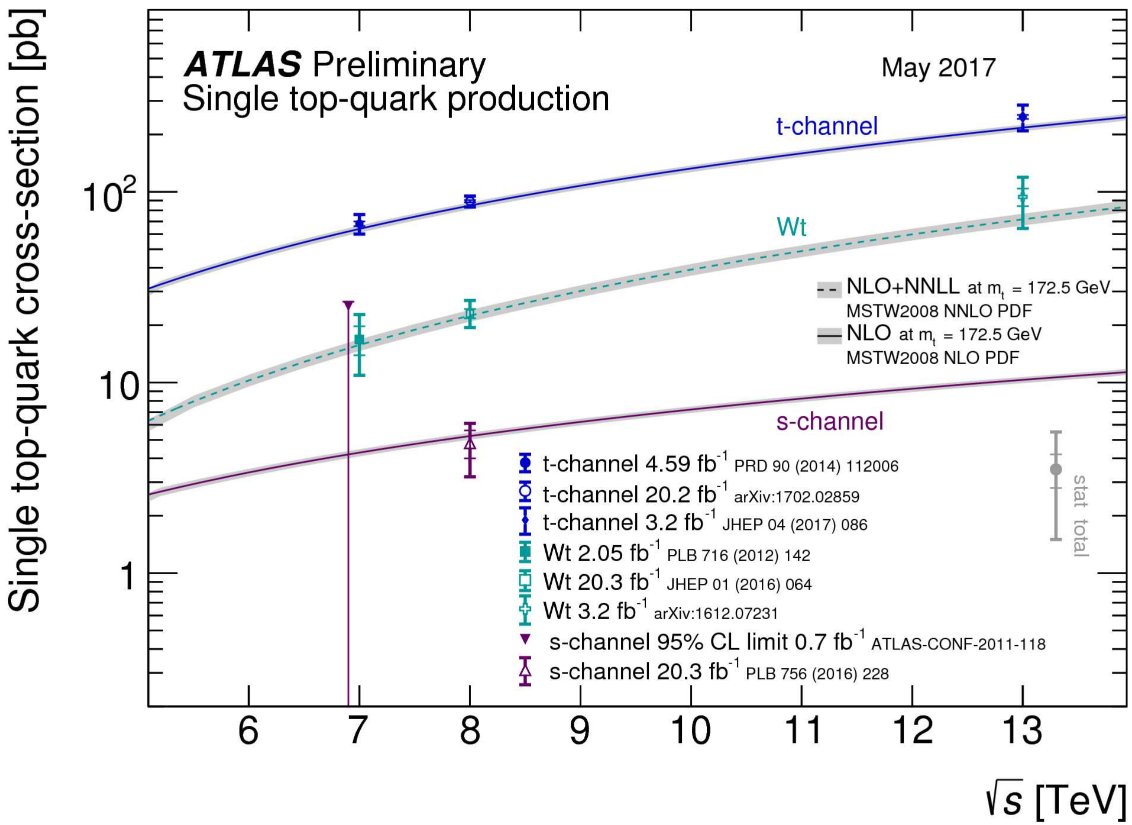
$$\sigma(tZq) = 600 \pm 170(stat.) \pm 140(syst.)\,fb$$
$$\text{observed (expected) significance}: 4.2\,\sigma\,(5.4\,\sigma)$$

$$\sigma_{theo}(tZq) = 800^{+49}_{-59}\,fb$$

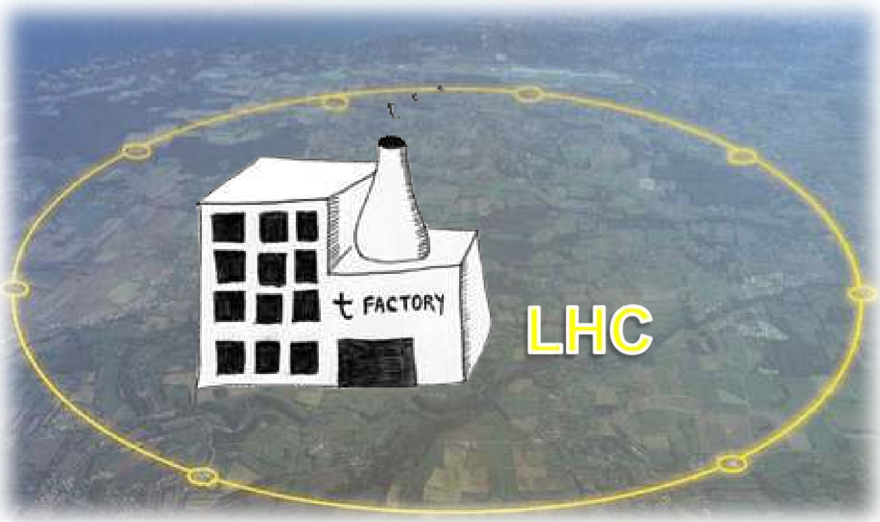


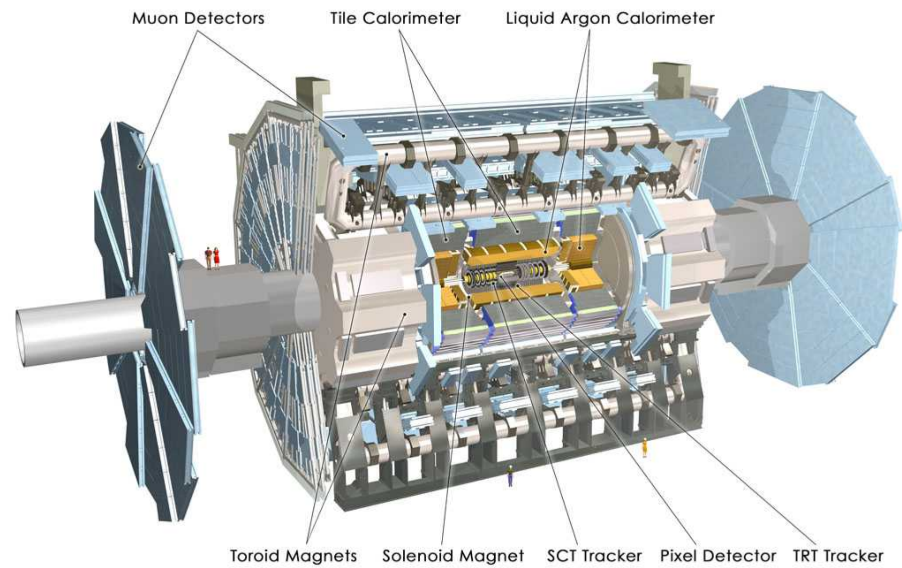
Summary

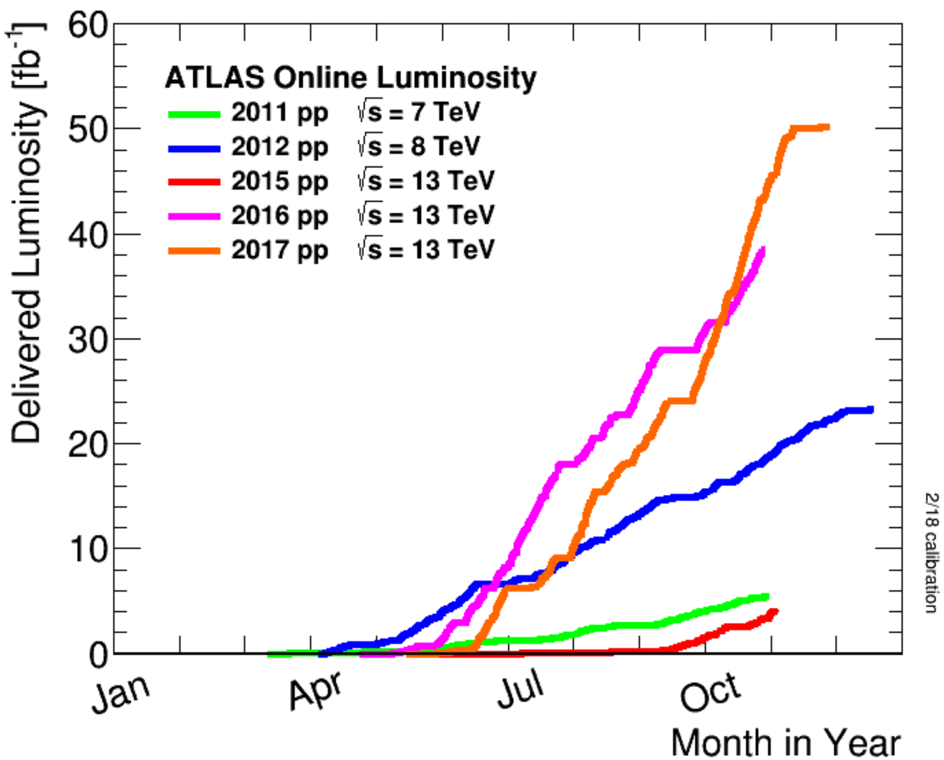
- ATLAS has studied comprehensively single-top-quark production at 8 TeV.
- Measurements are within uncertainties in agreement with theoretical predictions.
- First measurements at 13 TeV are coming out using 2015 and 2015+2016 data.
- New couplings can be accessed with 13 TeV luminosity **(evidence for tZq!)**
- Analyses will profit from full Run II dataset.

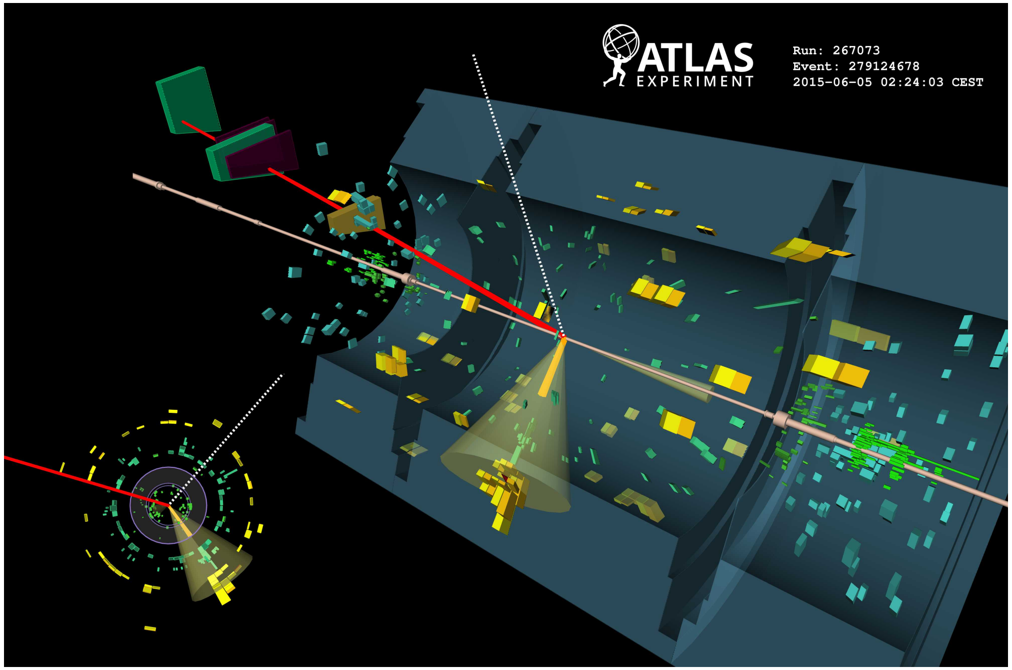


Backup


t FACTORY
LHC


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

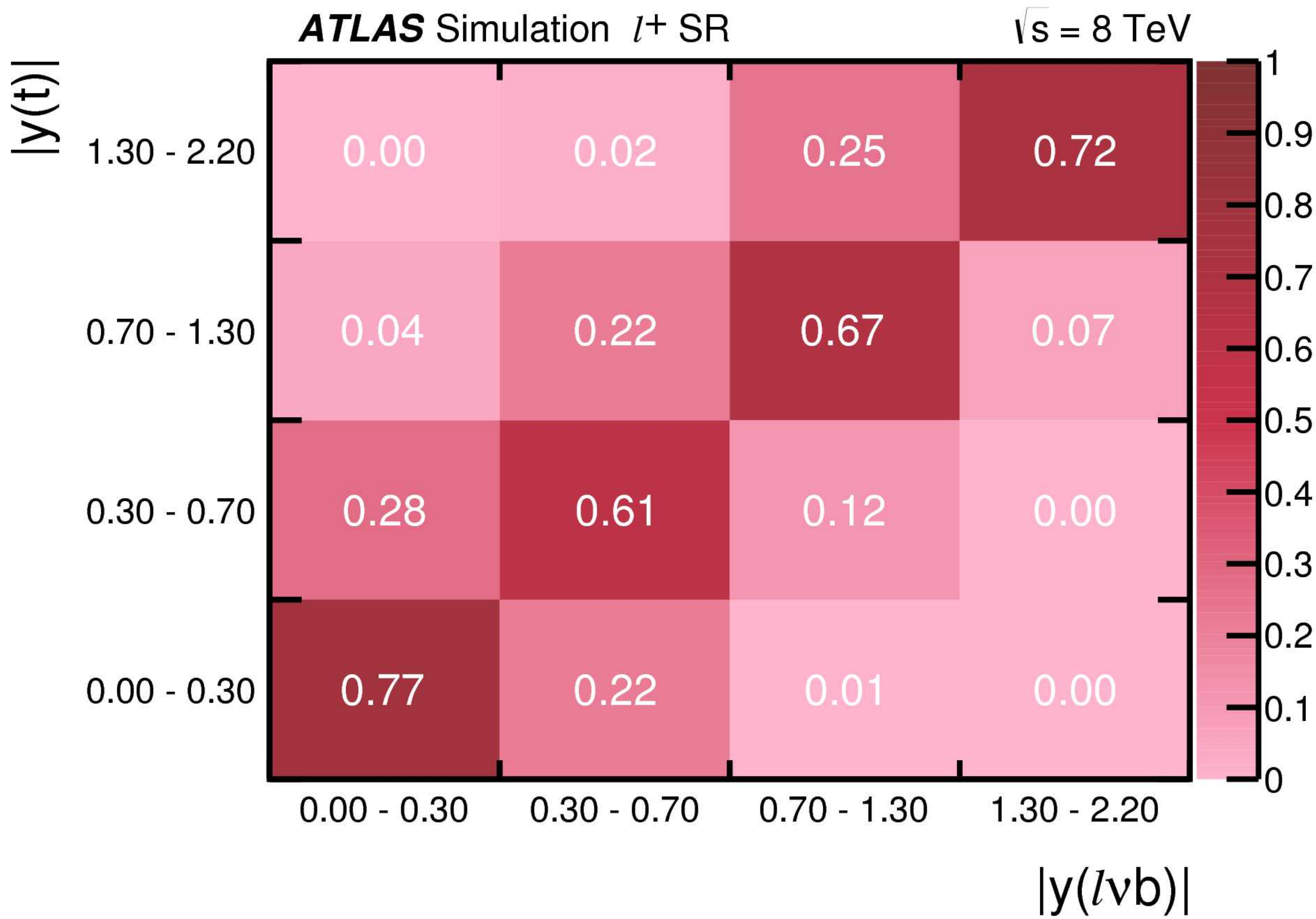

ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
Delivered Luminosity [fb^{-1}]
0
10
20
30
40
50
60
Jan
Apr
Jul
Oct
Month in Year
2/18 calibration


ATLAS
EXPERIMENT
Run: 267073
Event: 279124678
2015-06-05 02:24:03 CEST

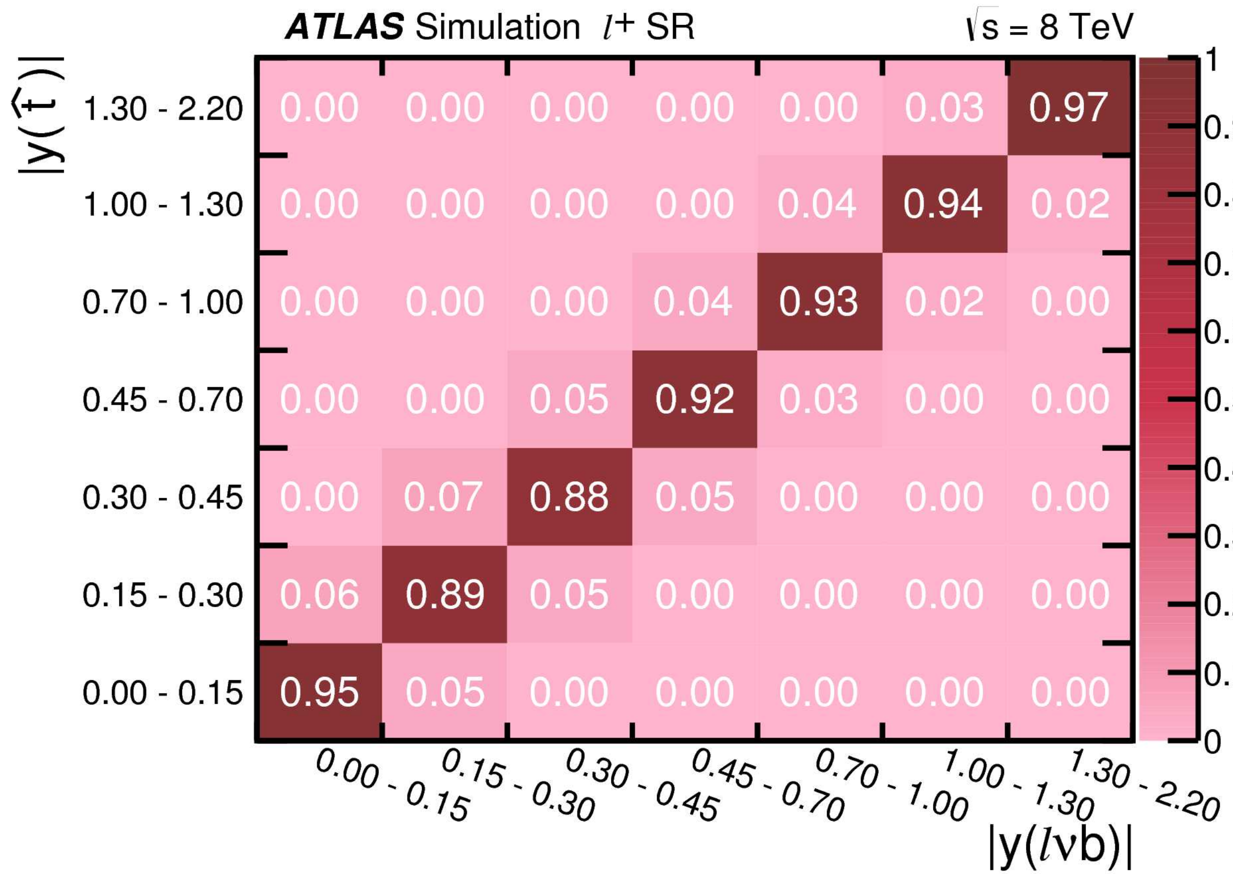
ATLAS measurements in this talk.

	8 TeV	13 TeV
t-channel	Eur. Phys. J. C 77 (2017) 531	JHEP04(2017)086
tW-channel	JHEP01(2016)064	JHEP 01 (2018) 63 Eur. Phys. J. C 78 (2018) 186
s-channel	PLB 756 (2016), 228-246	-
tZq	-	PLB 780 (2018), 557-577

- **Parton level.**
  - Before particles decay.
  - Measurement can be extrapolated to full phase space.
  - Compare the results with available theoretical predictions (not available at particle level).



- **Particle level.**
  - Leptons and jets are reconstructed from stable particles.
    - Lifetime > 3×10^{-11} s
    - Leptons : $P_T > 25$ GeV, $|\eta| < 2.5$.
    - Jets: $P_T > 30$ GeV, $|\eta| < 4.5$.
    - B-jets : $P_T > 30$ GeV, $|\eta| < 2.5$.
  - Before they interact with the detector.
  - Fiducial cuts on the objects similar to the reconstructed ones is able to:
    - Reduce modelling uncertainties.
    - Reduce dependencies from the generators.



Backup: t-channel uncertainties @ 8 TeV

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

Source	$\Delta R_t/R_t$ [%]
Data statistics	± 3.0
Monte Carlo statistics	± 1.8
Background modelling	± 0.7
Jet reconstruction	± 0.5
$E_{\text{T}}^{\text{miss}}$ 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

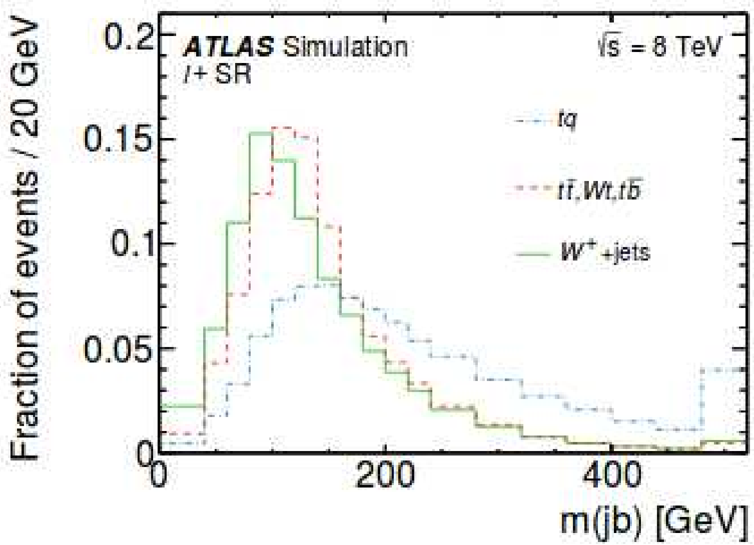
ABM Rt is 2.5 above ATLAS measurement. ABM PDF set differs from others sets in the treatment of the *b*-quark PDF and the value of alpha_s.

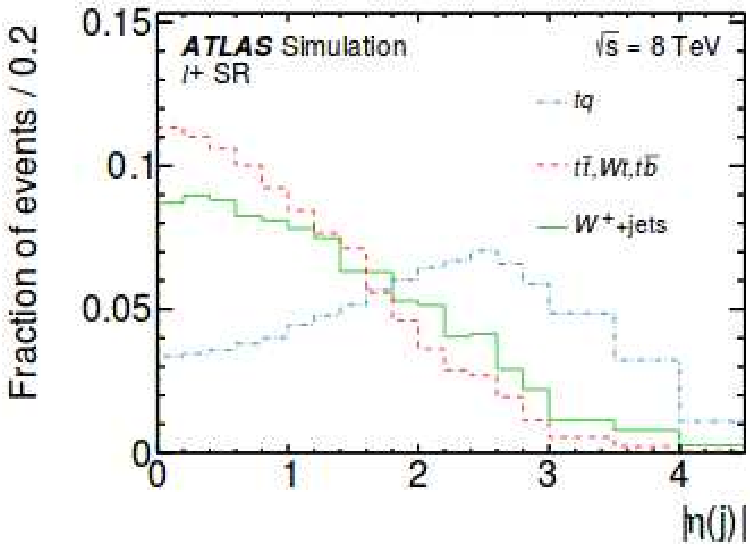
Backup: t-channel uncertainties @ 13 TeV

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_T^{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, $t\bar{b}+\bar{t}b$ 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

8 TeV input variables

Variable symbol	Definition
$m(jb)$	The invariant mass of the untagged jet (j) and the b-tagged jet (b).
$\|\eta(j)\|$	The absolute value of the pseudorapidity of the untagged jet.
$m(\ell\nu b)$	The invariant mass of the reconstructed top quark.
$m_{\mathrm{T}}(\ell E_{\mathrm{T}}^{\mathrm{miss}})$	The transverse mass of the lepton–$E_{\mathrm{T}}^{\mathrm{miss}}$ system, as defined in Eq. (2).
$\|\Delta\eta(\ell\nu, b)\|$	The absolute value of $\Delta\eta$ between the reconstructed W boson and the b-tagged jet.
$m(\ell b)$	The invariant mass of the charged lepton (ℓ) and the b-tagged jet.
$\cos\theta^{*}(\ell, j)$	The cosine of the angle, θ^{*}, between the charged lepton and the untagged jet in the rest frame of the reconstructed top quark.

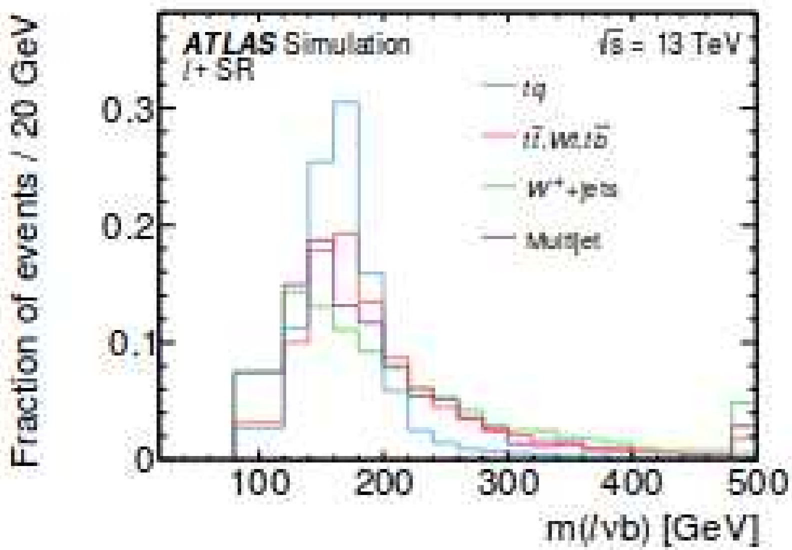


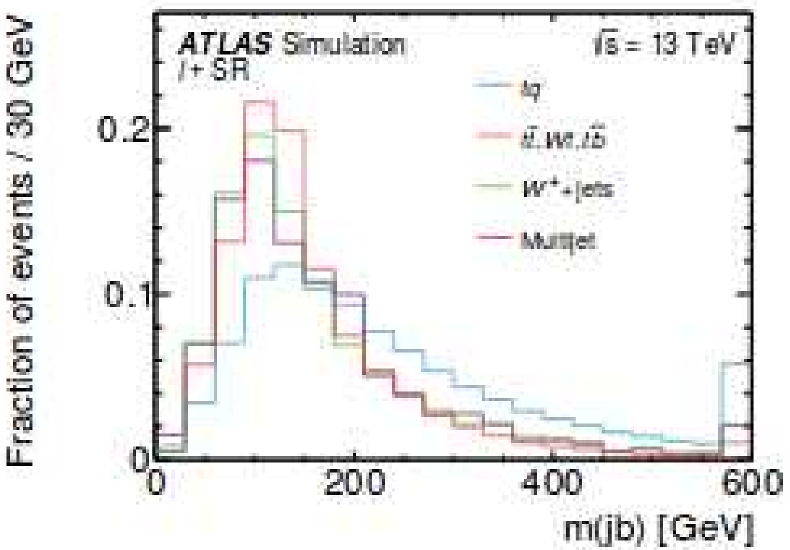


Backup: t-channel neural network

13 TeV input variables

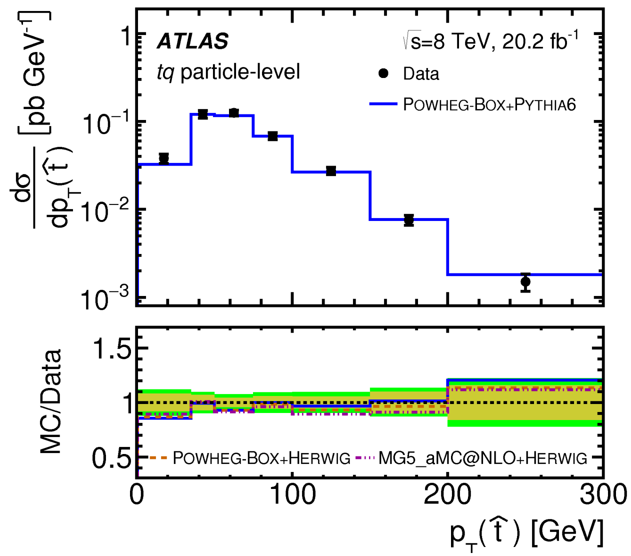
Variable	Definition
$m(\ell\nu b)$	top-quark mass reconstructed from the charged lepton, neutrino, and b-tagged jet
$m(jb)$	invariant mass of the b-tagged and untagged jet
$m_{\mathrm{T}}(\ell E_{\mathrm{T}}^{\mathrm{miss}})$	transverse mass of the reconstructed W boson
$\lvert\eta(j)\rvert$	modulus 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

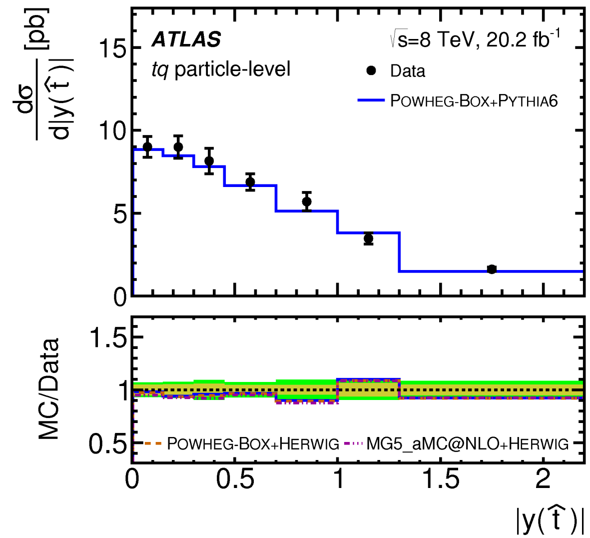


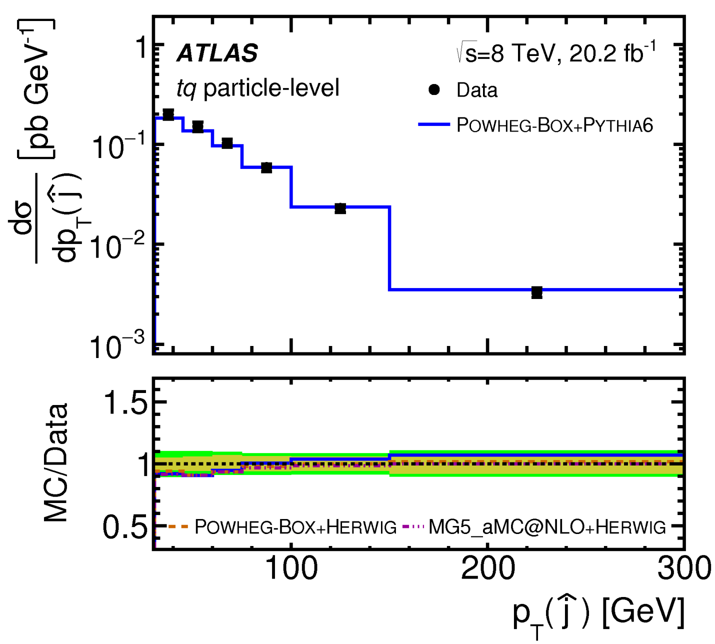


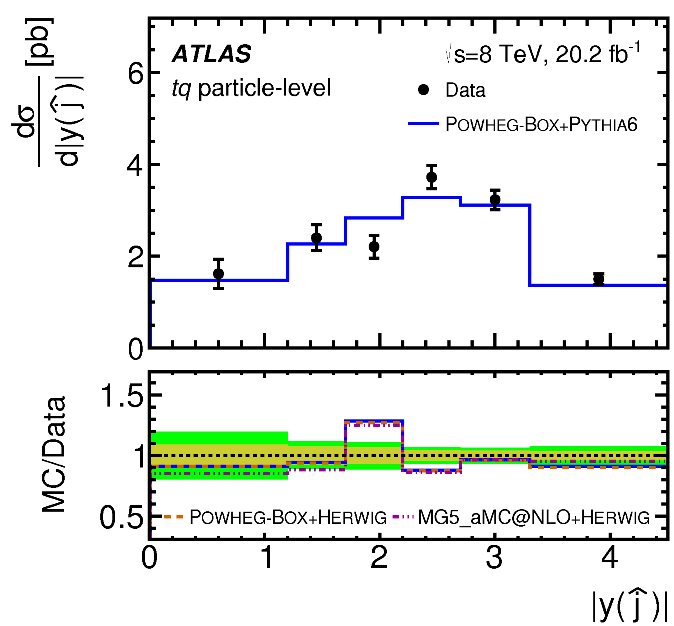
Backup: t-channel differential measurement @ 8 TeV.

Cross sections at particle level (only top shown).

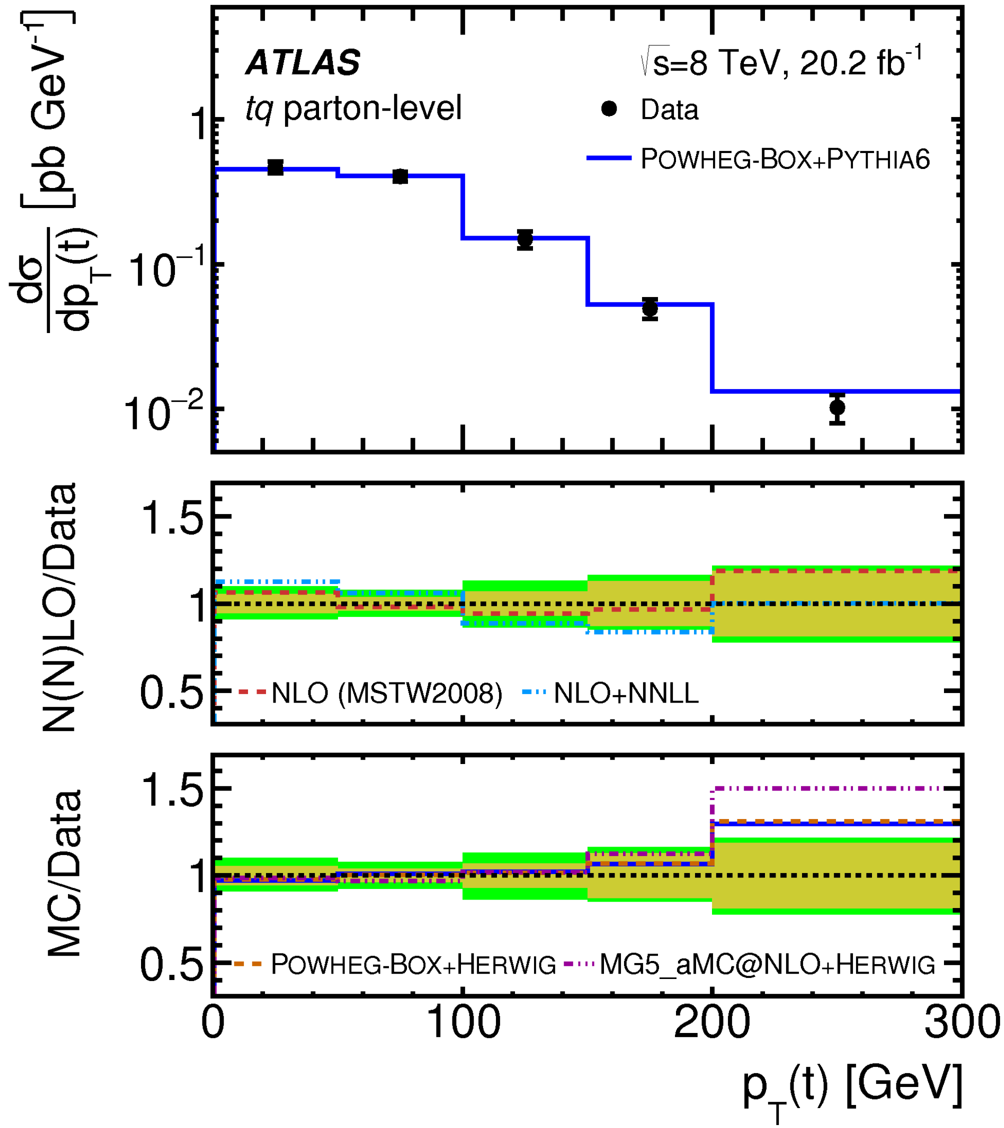


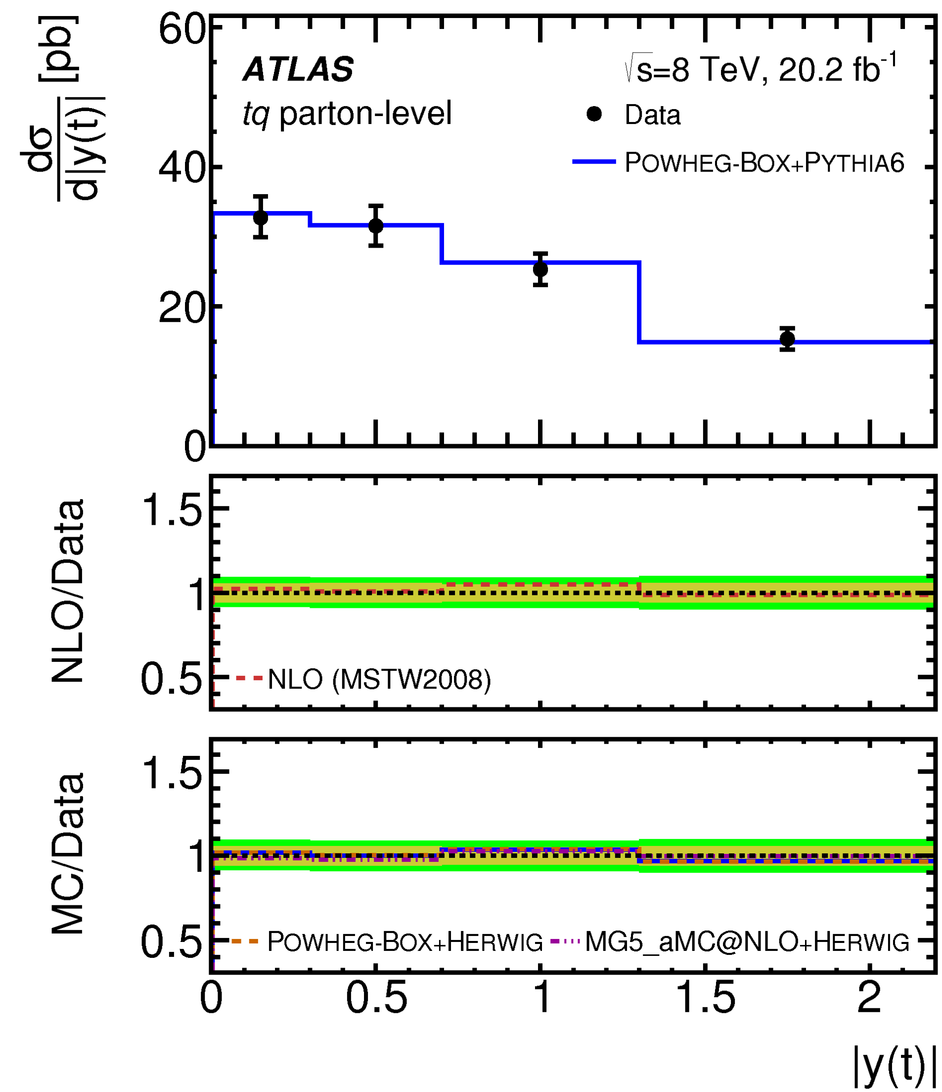




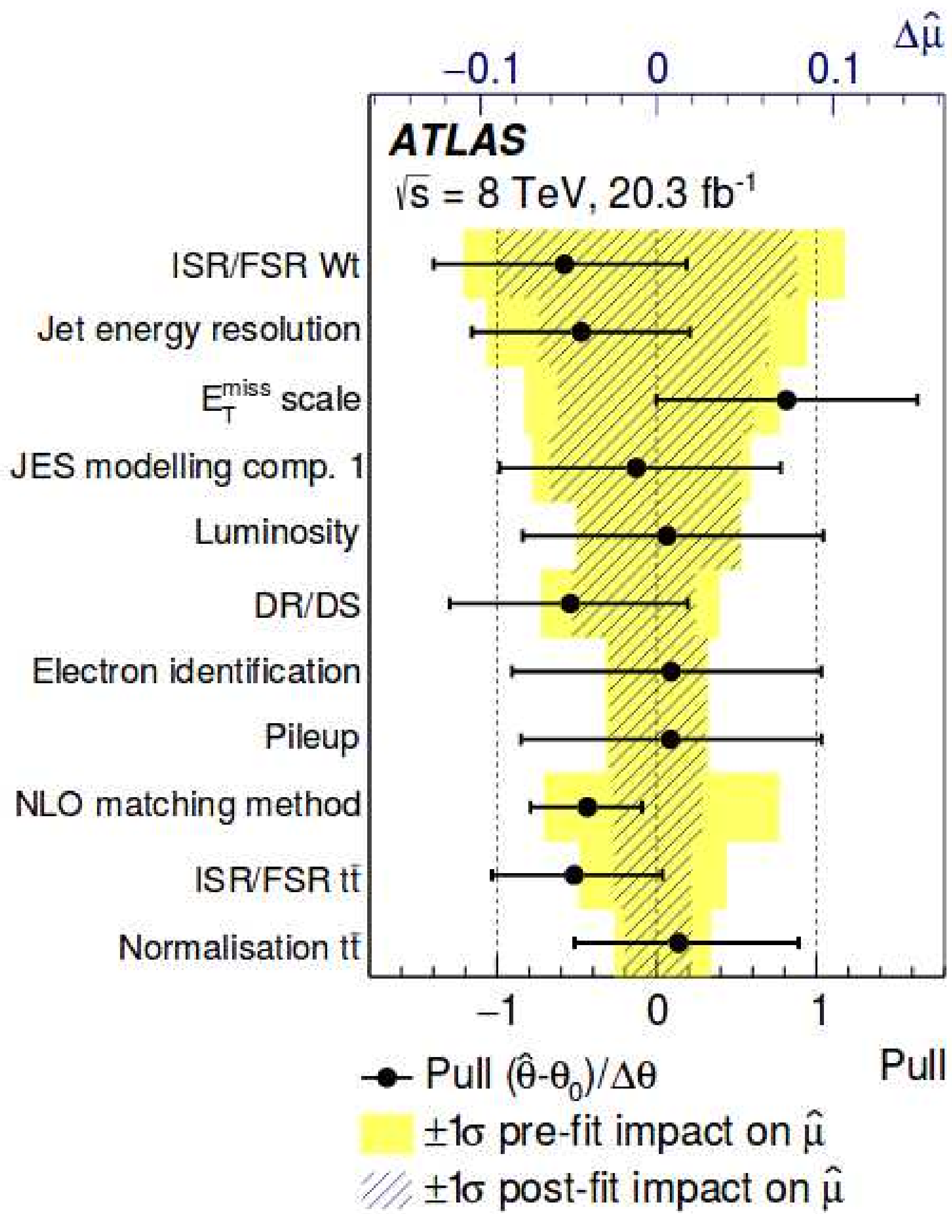


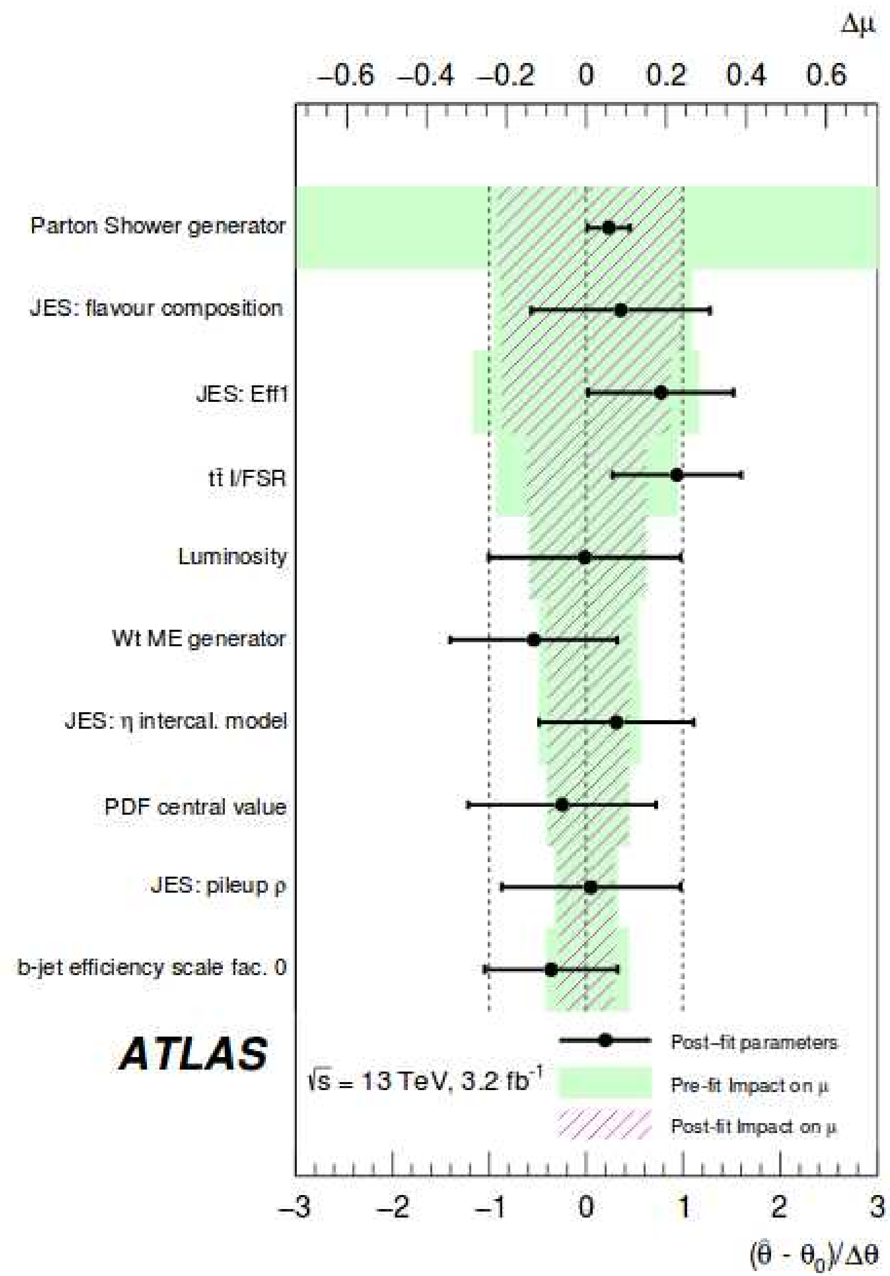
Cross sections at parton level (only top shown).





Backup: tW-channel fit impact comparison on uncertainties



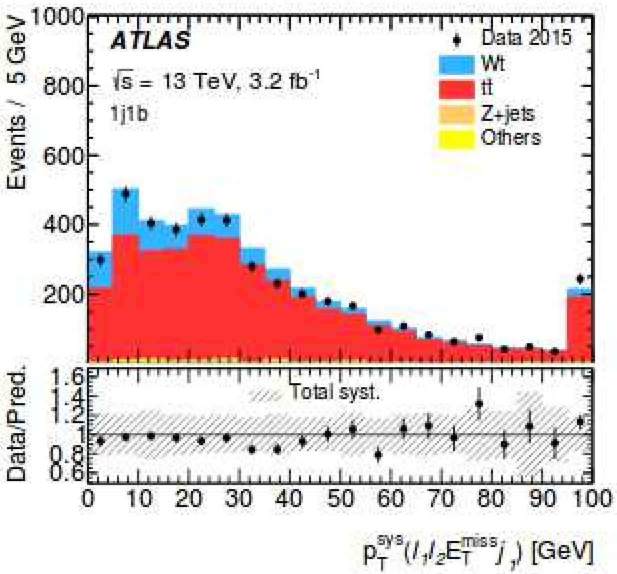


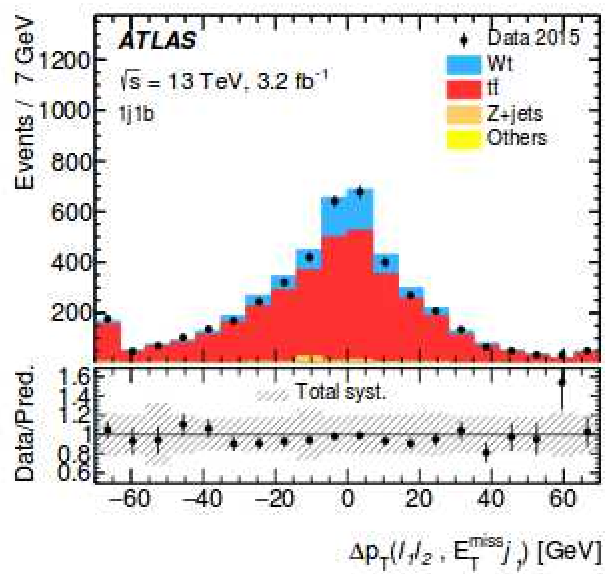
Backup: tW-channel event selection and uncertainties @ 13 TeV.

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

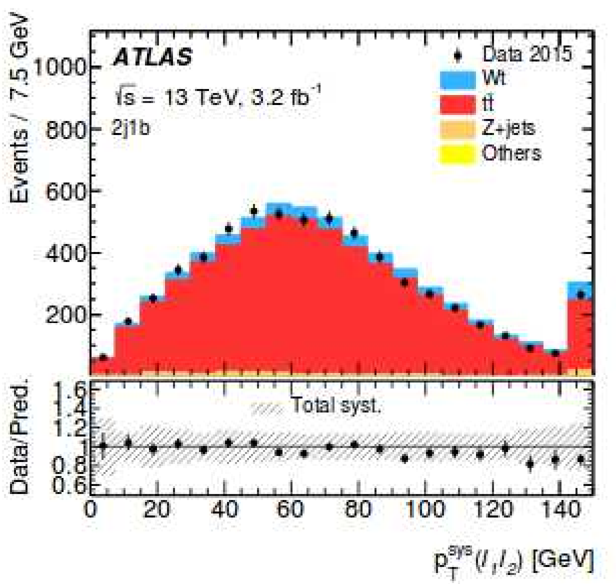
Source	$\Delta\sigma_{Wt}/\sigma_{Wt}$[%]
Jet energy scale	21
Jet energy resolution	8.6
E_T^{miss} soft terms	5.3
b-tagging	4.3
Luminosity	2.3
Lepton efficiency, energy scale and resolution	1.3
NLO matrix element generator	18
Parton shower and hadronisation	7.1
Initial-/final-state radiation	6.4
Diagram 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

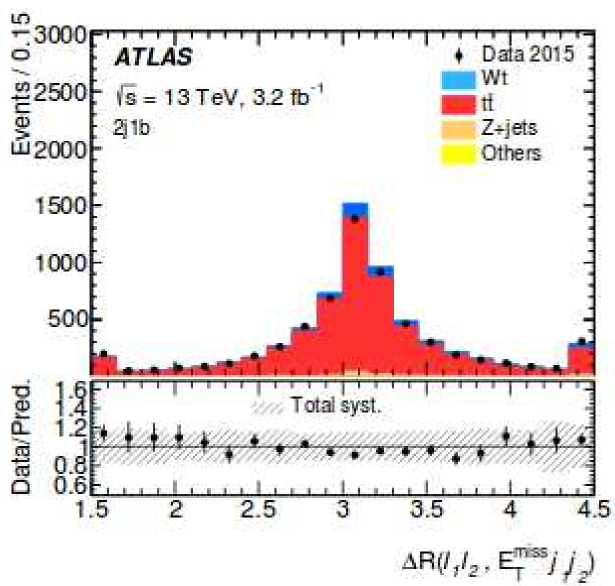
Backup: tW-channel BDT discriminating power @ 13 TeV.





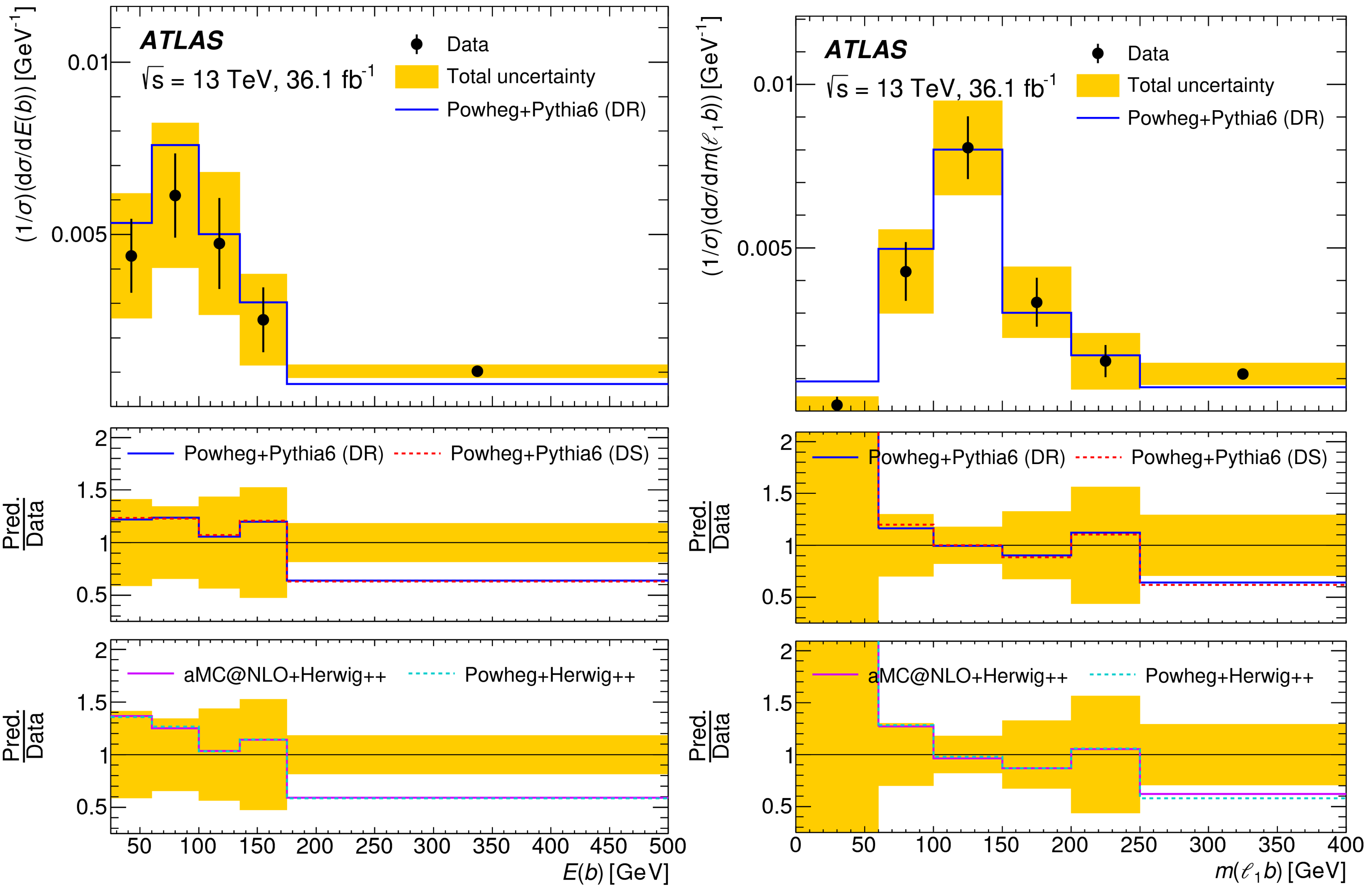
1j1b	
Variable	S $[10^{-2}]$
$p_{\mathrm{T}}^{\mathrm{sys}}(\ell_1\ell_2E_{\mathrm{T}}^{\mathrm{miss}}j_1)$	5.3
$\Delta p_{\mathrm{T}}(\ell_1\ell_2, E_{\mathrm{T}}^{\mathrm{miss}}j_1)$	2.9
$\sum E_{\mathrm{T}}$	2.7
$\Delta p_{\mathrm{T}}(\ell_1\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$	1.2
$p_{\mathrm{T}}^{\mathrm{sys}}(\ell_1E_{\mathrm{T}}^{\mathrm{miss}}j_1)$	0.9
$C(\ell_1\ell_2)$	0.9
$\Delta p_{\mathrm{T}}(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}})$	0.8
BDT discriminant	8.6



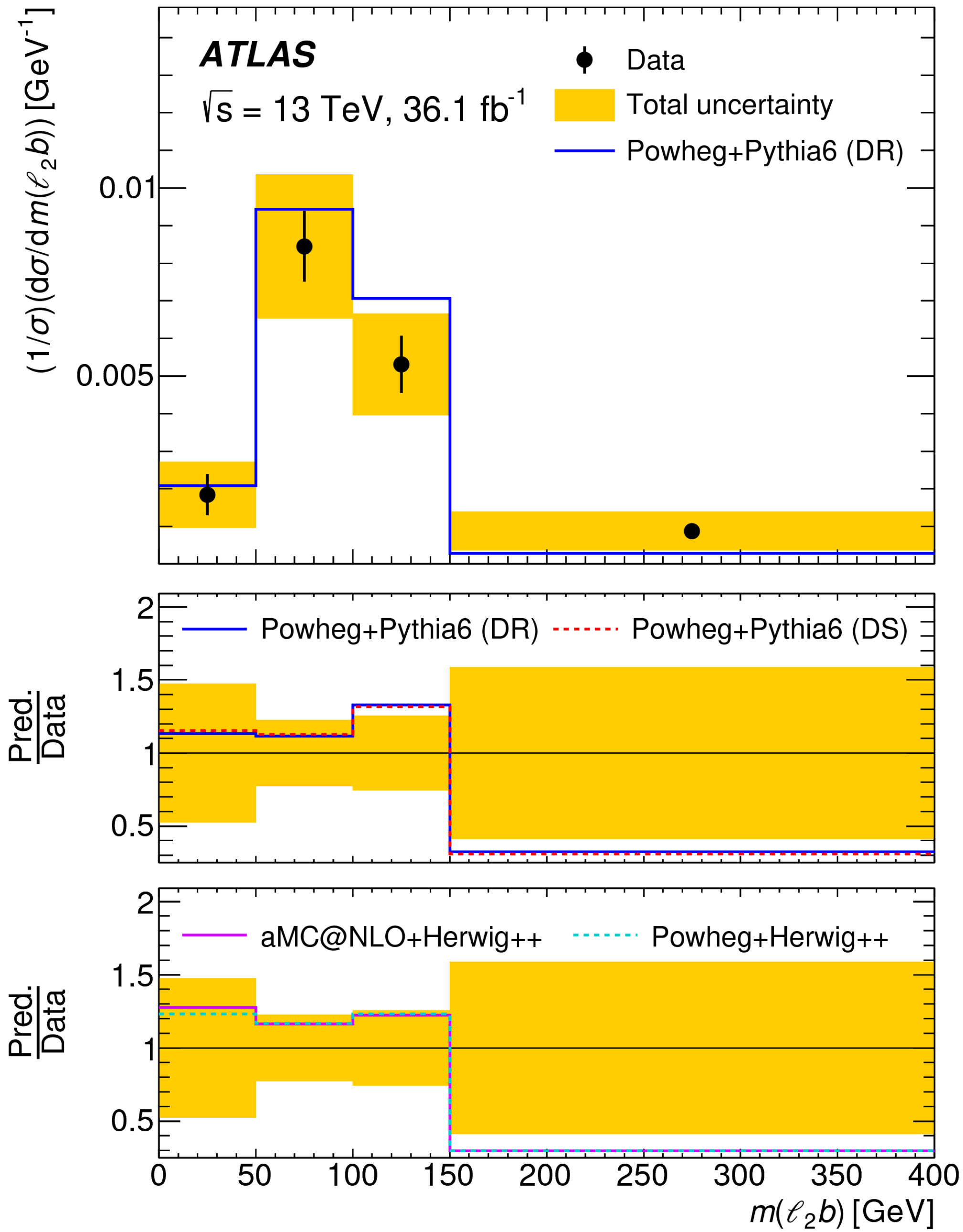


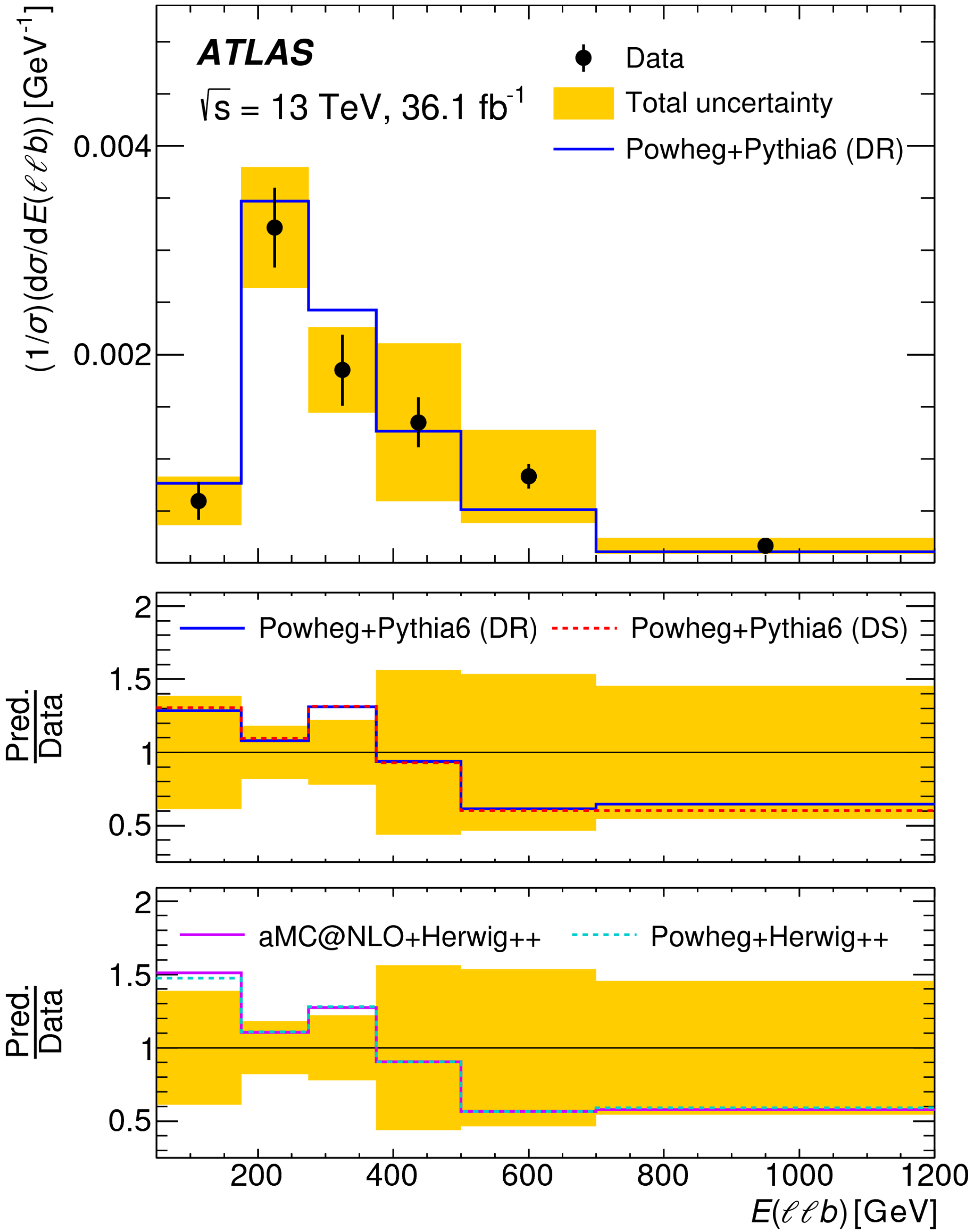
2j1b	
Variable	S $[10^{-2}]$
$p_{\mathrm{T}}^{\mathrm{sys}}(\ell_1\ell_2)$	1.7
$\Delta R(\ell_1\ell_2, E_{\mathrm{T}}^{\mathrm{miss}}j_1j_2)$	1.7
$\Delta R(\ell_1\ell_2, j_1j_2)$	1.5
$m(\ell_1j_2)$	1.4
$\Delta p_{\mathrm{T}}(\ell_1\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$	1.4
$\Delta p_{\mathrm{T}}(\ell_1, j_1)$	1.4
$m(\ell_1j_1)$	1.3
$p_{\mathrm{T}}(\ell_1)$	1.3
$\sigma(p_{\mathrm{T}}^{\mathrm{sys}})(\ell_1\ell_2E_{\mathrm{T}}^{\mathrm{miss}}j_1)$	1.2
$\Delta R(\ell_1, j_1)$	1.2
$p_{\mathrm{T}}(j_2)$	0.9
$\sigma(p_{\mathrm{T}}^{\mathrm{sys}})(\ell_1\ell_2E_{\mathrm{T}}^{\mathrm{miss}}j_1j_2)$	0.9
$m(\ell_2j_1j_2)$	0.3
$m(\ell_2j_1)$	0.3
$m(\ell_2j_2)$	0.1
BDT discriminant	10.9

Backup: tW-channel differential measurement @13 TeV.

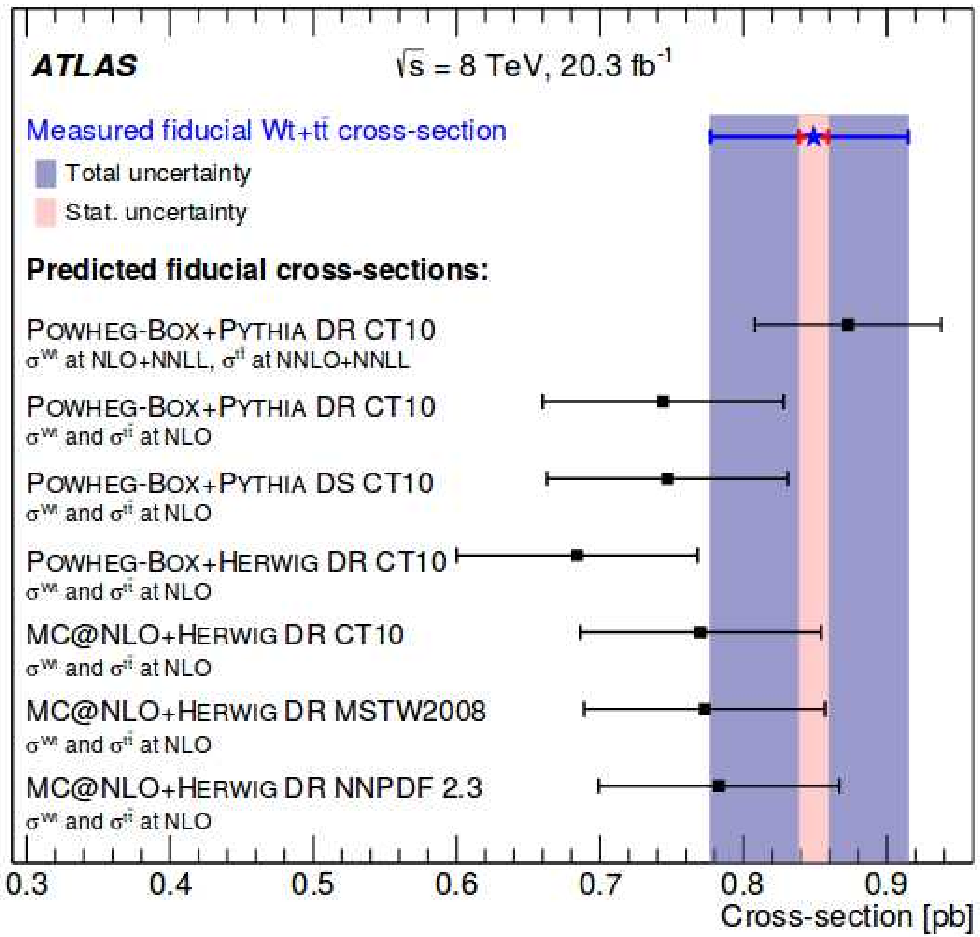


Backup: tW-channel differential measurement @13 TeV.



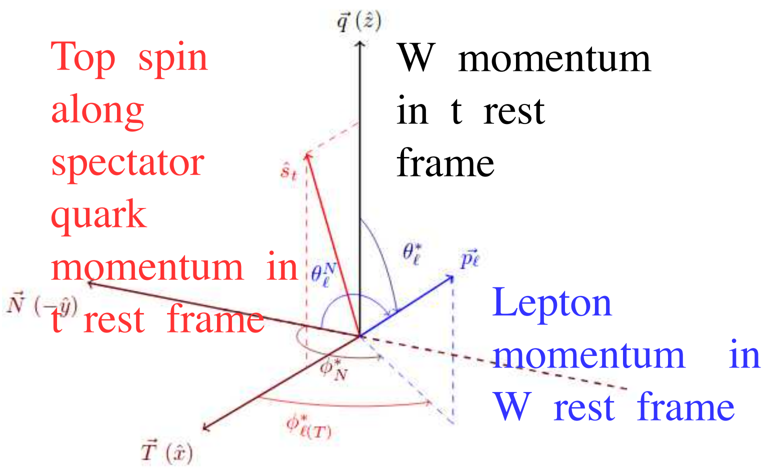


Backup: tW-channel fiducial measurement @ 8 TeV.

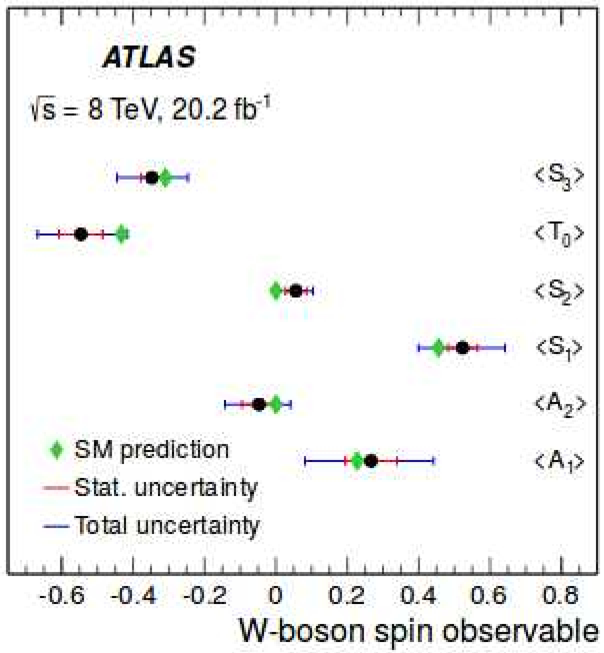


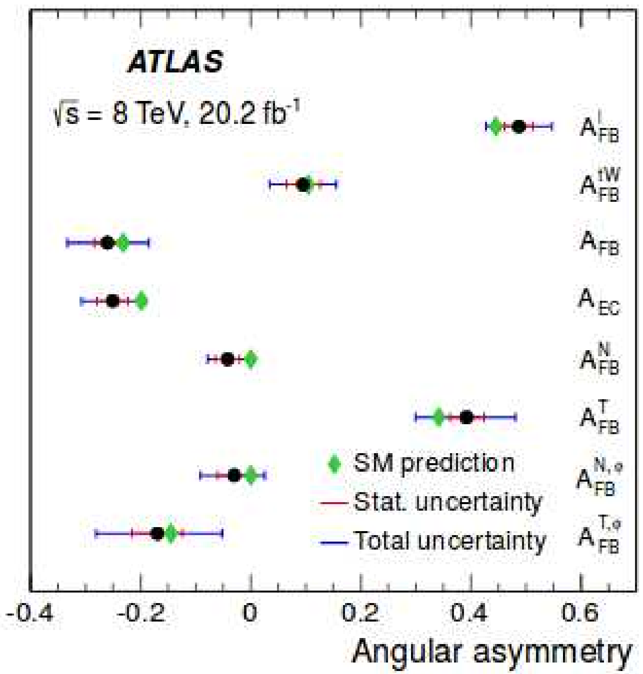
Uncertainty	Impact on $\hat{\mu}_{\text{fid}}$ [%]
Statistical	1.0
Luminosity	3.1
Theory modelling	
ISR/FSR	4.2
Hadronisation	0.8
NLO matching method	0.7
PDF	<0.1
Ratio $Wt/t\bar{t}$	2.2
DR/DS	0.1
Detector	
Jet	5.2
Lepton	2.3
$E_{\text{T}}^{\text{miss}}$	0.2
b-tag	2.3
Background norm.	<0.1
Total	8.2

Backup: Polarization definitions and results.

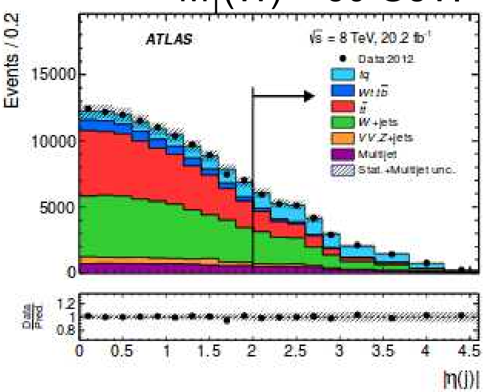


Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P(F_R + F_L)$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}(F_R - F_L)$	−0.23
A_{EC}	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}(1 - 3F_0)$	−0.20
A_{FB}^{T}	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
A_{FB}^{N}	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{FB}^{T,\phi}$	$\cos\theta_\ell^* \cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A_{FB}^{N,\phi}$	$\cos\theta_\ell^* \cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0

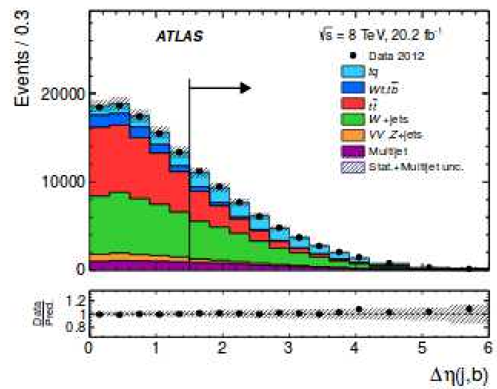




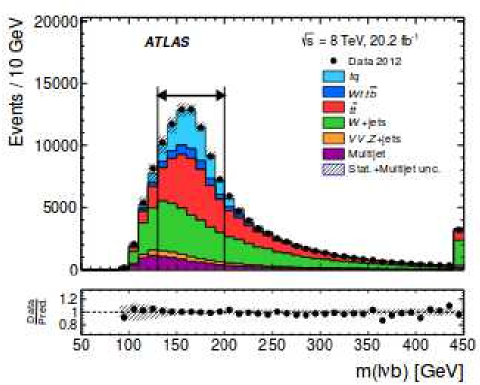
- **Preselection cuts.**
  - Exactly one lepton.
  - Exactly two jets, one being tagged (2j1b).
  - MET > 30 GeV.
  - $M_T(W)$ > 50 GeV.

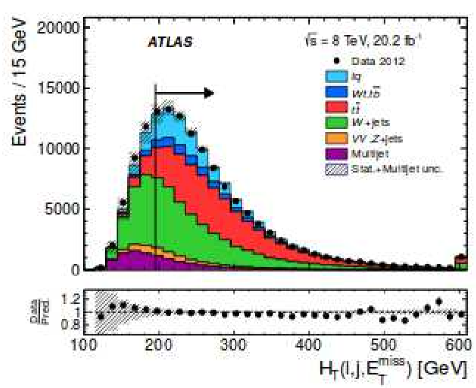


- **|η(j)| > 2**



- **|Δη(j,b)| > 1.5**





- **130GeV < m(lνb) < 200 GeV**
- **H_T > 200 GeV**

Uncertainties

Uncertainty source	$\Delta A_{FB}^{\ell} \times 10^2$
Statistical uncertainty	±2.6
Simulation statistics	±1.7
Luminosity	<0.1
Background normalisation	±0.5
E_T^{miss} reconstruction	$^{+0.9}_{-0.1}$
Lepton reconstruction	$^{+1.0}_{-0.4}$
Jet reconstruction	±2.1
Jet energy scale	$^{+1.3}_{-1.2}$
Jet flavour tagging	±0.9
PDF	±0.2
$t\bar{t}$ generator	±2.3
$t\bar{t}$ parton shower	±0.6
$t\bar{t}$ scales	±0.2
Wt, s-channel generator	±1.0
Wt, s-channel scales	±0.9
t-channel NLO generator	±1.4
t-channel LO–NLO generator	±1.5
t-channel parton shower	±0.5
t-channel scales	±1.1
W+jets, multijet modelling	$^{+1.9}_{-2.4}$
Total systematic uncertainty	$^{+5.4}_{-5.4}$

Uncertainty source	$\Delta A_{FB}^{N} \times 10^2$
Statistical uncertainty	±2.2
Simulation statistics	±1.3
Luminosity	<0.1
Background normalisation	±0.4
E_T^{miss} reconstruction	$^{+0.3}_{-0.4}$
Lepton reconstruction	$^{+0.1}_{-0.2}$
Jet reconstruction	±0.8
Jet energy scale	$^{+0.9}_{-0.8}$
Jet flavour tagging	±0.2
PDF	±0.1
$t\bar{t}$ generator	±0.2
$t\bar{t}$ parton shower	±1.5
$t\bar{t}$ scales	±0.3
Wt, s-channel generator	±0.2
Wt, s-channel scales	±0.6
t-channel NLO generator	±0.3
t-channel LO–NLO generator	±0.5
t-channel parton shower	±0.7
t-channel scales	±0.9
W+jets, multijet modelling	$^{+0.7}_{-0.6}$
Total systematic uncertainty	$^{+2.9}_{-2.9}$

- **Main systematics:** ttbar modelling, jet calibration, MC statistics.

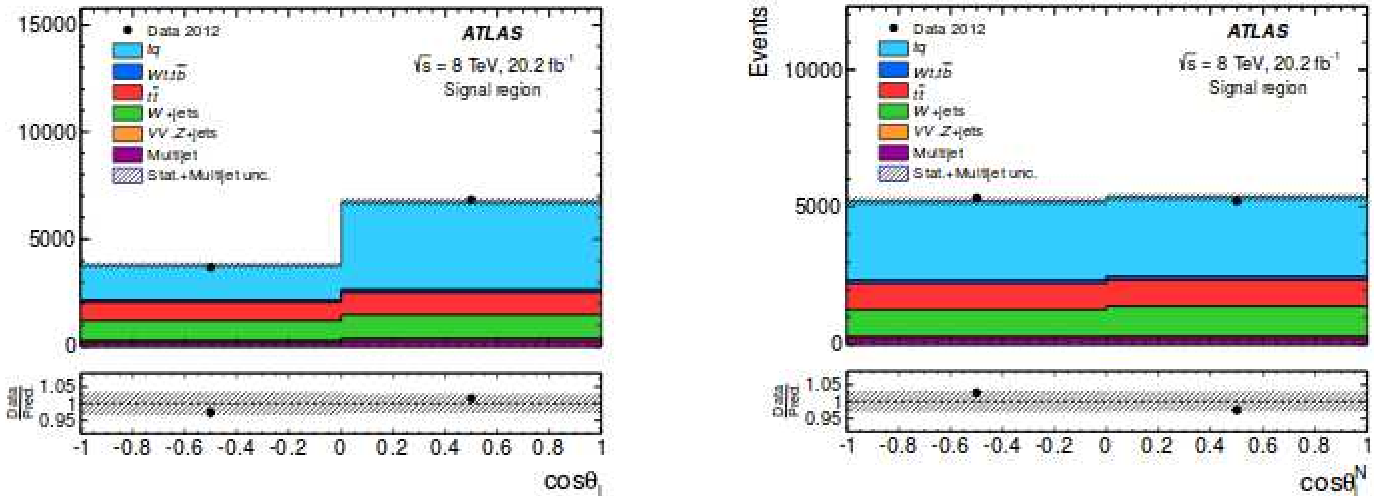
- **Probe Wtb vertex structure in the t-channel using angular asymmetries.**

$$A_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + \text{h.c.}$$

In the SM:
$V_L = V_{tb}$
anomalous couplings = 0.

- **Main backgrounds:**
  - **ttbar**, **W+jets**.
  - E_T^{MISS} used to supress **multijet** contributions.
- **Combined maximum likelihood fit over signal and control regions.**



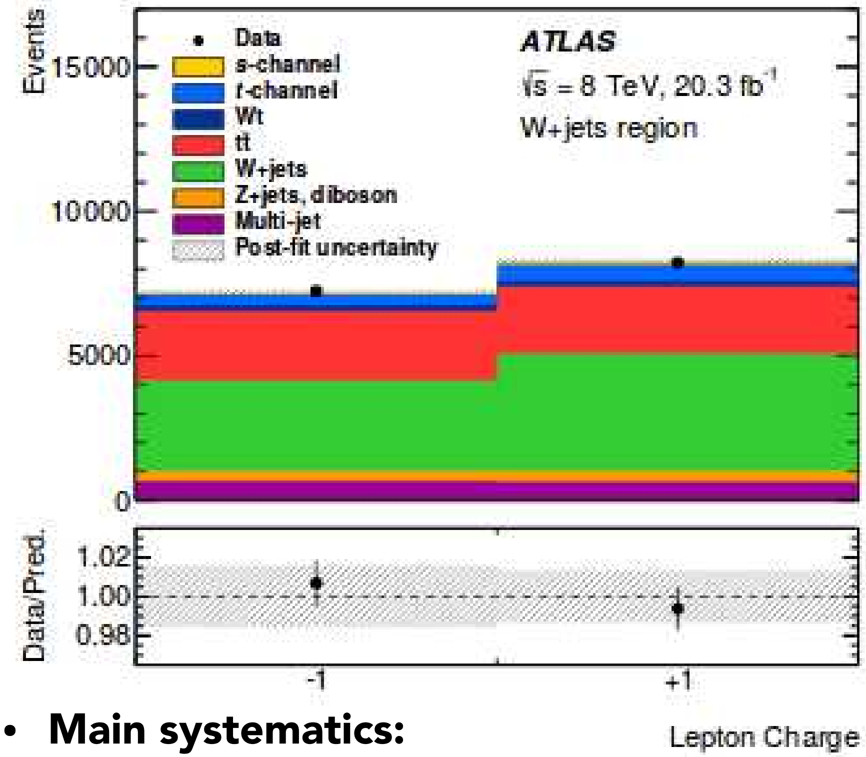
- **Unfolding to parton level.**
- A_{FB}^{N} and A_{FB}^{l} used to set **limits on anomalous** couplings and compute **top-quark polarization**:

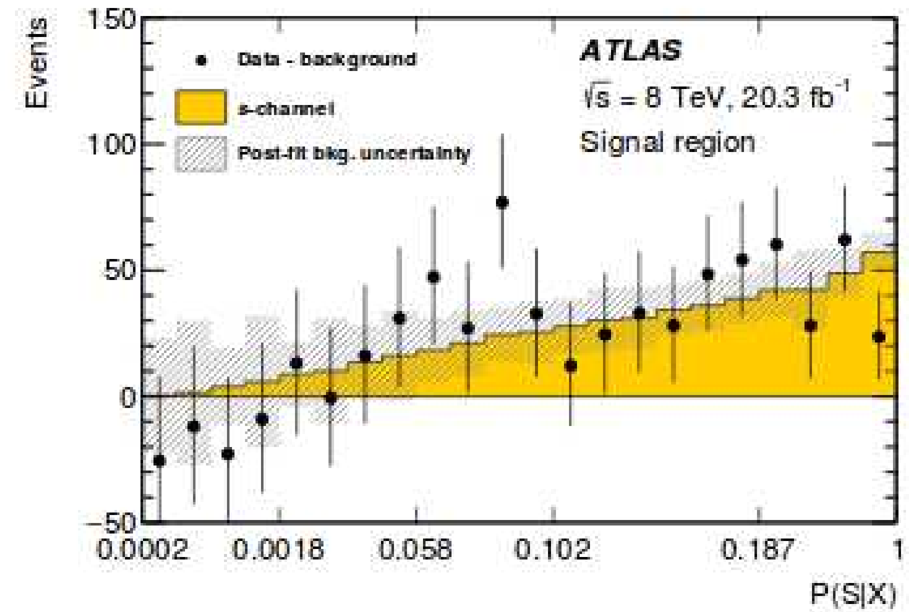
$$\mathrm{Im}(g_R) \in [-0.18, 0.06] \text{ at } 95\% \text{ CL}$$
$$\text{if } V_L = 1; V_R = g_L = \mathrm{Re}(g_R) = 0$$

$$\alpha_l P = 0.97 \pm 0.05(\text{stat.}) \pm 0.11(\text{syst.})$$
$$\alpha_l = 0.998 (\text{at NLO}) \quad P_t = 0.91 (\text{at NLO})$$

Backup: s-channel total measurement @ 8 TeV.

- **Lepton charge distribution in control region used to better constraint W+jets from other backgrounds.**





- **Main systematics:**
  - MC statistics (12%).
  - jet enegy resolution (12%) .
  - t-channel modelling (11%).

tZq @ 13 TeV: event selection and main uncertainties.

EVENT SELECTION:

Common selections			
exactly 3 leptons with $\|\eta\| < 2.5$ and $p_T > 15$ GeV $p_T(\ell_1) > 28$ GeV, $p_T(\ell_2) > 25$ GeV, $p_T(\ell_3) > 15$ GeV $p_T(\text{jet}) > 30$ GeV $m_T(\ell_W, \nu) > 20$ GeV			
SR	**Diboson VR / CR**	**$t\bar{t}$ VR**	**$t\bar{t}$ CR**
≥ 1 OSSF Pair	≥ 1 OSSF Pair	≥ 1 OSSF Pair	≥ 1 OSOF Pair
$\|m_{\ell\ell} - m_Z\| < 10$ GeV	$\|m_{\ell\ell} - m_Z\| < 10$ GeV	$\|m_{\ell\ell} - m_Z\| > 10$ GeV	—
= 2 jets, $\|\eta\| < 4.5$	= 1 jet, $\|\eta\| < 4.5$	= 2 jets, $\|\eta\| < 4.5$	= 2 jets, $\|\eta\| < 4.5$
= 1 b-jet, $\|\eta\| < 2.5$	—	= 1 b-jet, $\|\eta\| < 2.5$	= 1 b-jet, $\|\eta\| < 2.5$
—	VR/CR: $m_T(\ell_W, \nu) > 20/60$ GeV	—	—

UNCERTAINTIES:

Source	Uncertainty [%]
tZq radiation	±10.8
Jets	±4.6
Luminosity	±3.2
b-tagging	±2.9
MC statistics	±2.8
Leptons	±2.1
tZq PDF	±1.2
E_T^{miss}	±0.3