

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

Carl Suster

on behalf of the ATLAS Collaboration

Pheno2017, Pittsburgh: May 8–10, 2017



THE UNIVERSITY OF  
SYDNEY

# Single top quark production

- Single top quark production:  
discovered at Tevatron (2009),  
observed at LHC (2011)
- Charged-current EW processes
- $Wtb$  vertex:
  - access to CKM element  $|V_{tb}|$
  - vertex structure is sensitive to BSM physics
- Can constrain PDFs
- Tune MC generators (unfolded distributions)

*Theory cross-sections shown*

Kidonakis (2011); Kidonakis (2010);  
Campbell et al. (2009); Kidonakis (2015)

$t$ -channel

$$\sigma_{8 \text{ TeV}} = 87.7^{+3.4}_{-1.9} \text{ pb}$$

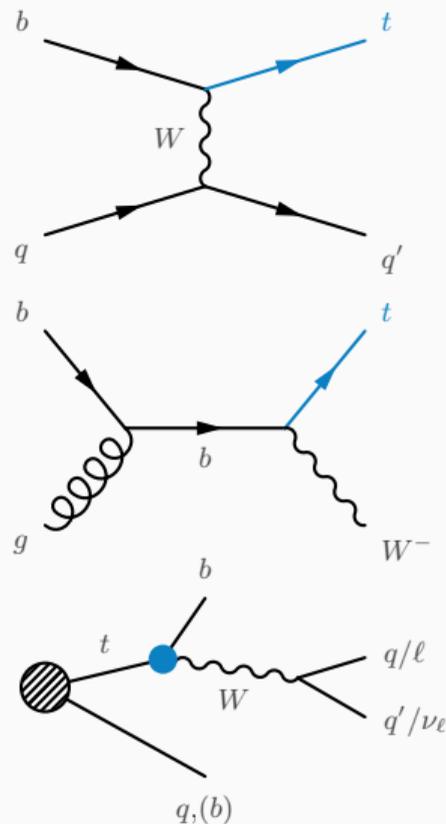
$$\sigma_{13 \text{ TeV}} = 217.0^{+9.1}_{-7.7} \text{ pb}$$

$tW$  associated

$$\sigma_{8 \text{ TeV}} = 22.4 \pm 1.5 \text{ pb}$$

$$\sigma_{13 \text{ TeV}} = 71.1 \pm 3.9 \text{ pb}$$

anomalous coupling



## Channels and measurements covered here

- ATLAS has a [comprehensive](#) single top physics program
- Recent 8 TeV and 13 TeV cross-section results for  $t$ -channel and  $tW$  covered here

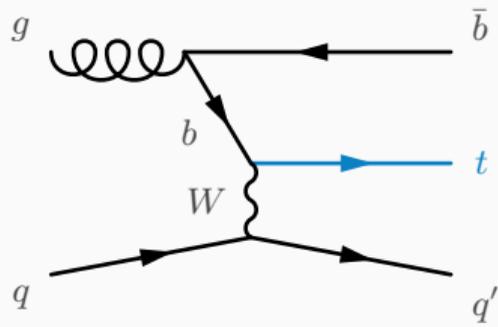
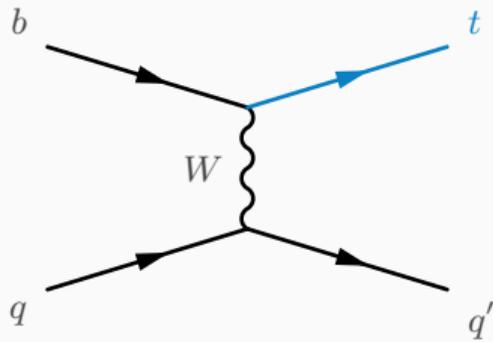
---

$\sqrt{s}$	$s$ -channel	$t$ -channel	$tW$	anomalous coupling
7 TeV	ATLAS-CONF-2011-118	PRD 90, 112006 (2014)	ATLAS-CONF-2011-104	JHEP04(2016)023
8 TeV	PLB (2016), 228-246	<a href="#">arXiv:1702.02859</a>	<a href="#">JHEP01(2016)064</a>	<a href="#">arXiv:1702.08309</a>
13 TeV		<a href="#">JHEP04(2017)086</a>	<a href="#">arXiv:1612.07231</a>	

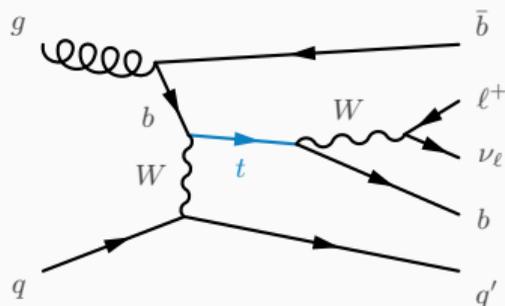
---

## $t$ -channel

---



## $t$ -channel production

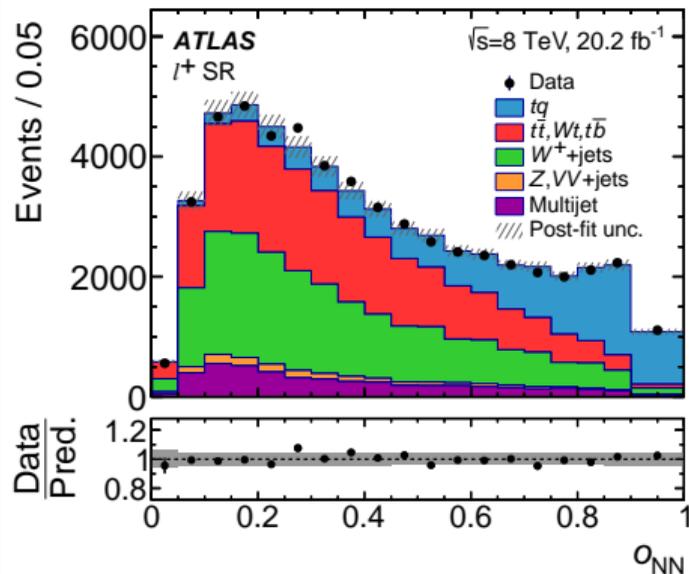


8 TeV	1j	2j	3j
0b			
1b <sub>loose</sub>		VR Wj	
1b		SR	
2b		VR t $\bar{t}$	

SR = signal region, VR = validation

- Exchange of  $W$  boson in the  $t$ -channel
- Largest cross-section of single top for  $pp$
- Signature of the leptonic final state:
  - 1 isolated lepton
  - $E_T^{\text{miss}}$  from the neutrino
  - 1 high- $p_T$  forward jet ( $q$ )
  - 1 high- $p_T$   $b$ -tagged jet
- Main backgrounds:  $t\bar{t}$ ,  $W$  + jets, multijet
- Neural network to enhance signal extraction

- 2012 dataset:  $20.2 \text{ fb}^{-1}$  at 8 TeV
  - Fiducial and total cross-sections
  - Differential cross-sections
- 2015 dataset:  $3.2 \text{ fb}^{-1}$  at 13 TeV
  - Total cross-section
- $tq$  and  $\bar{t}q$  are measured separately
- Signal regions:  $\ell^+$  and  $\ell^-$  respectively

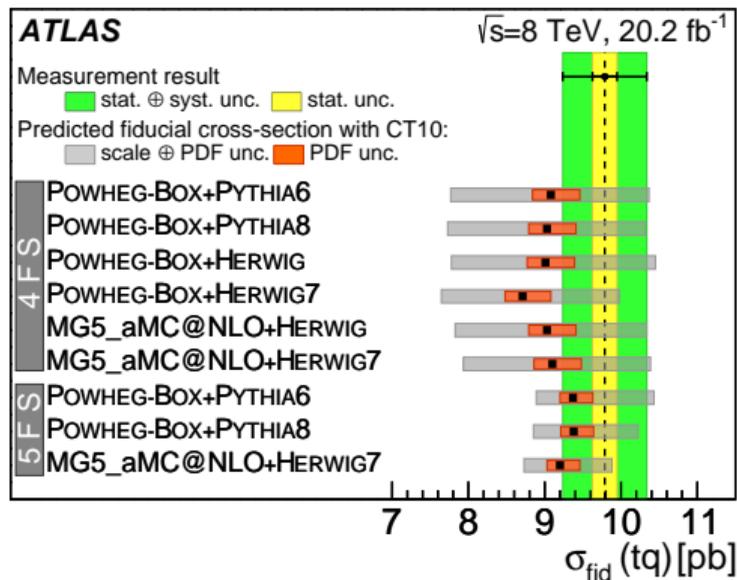


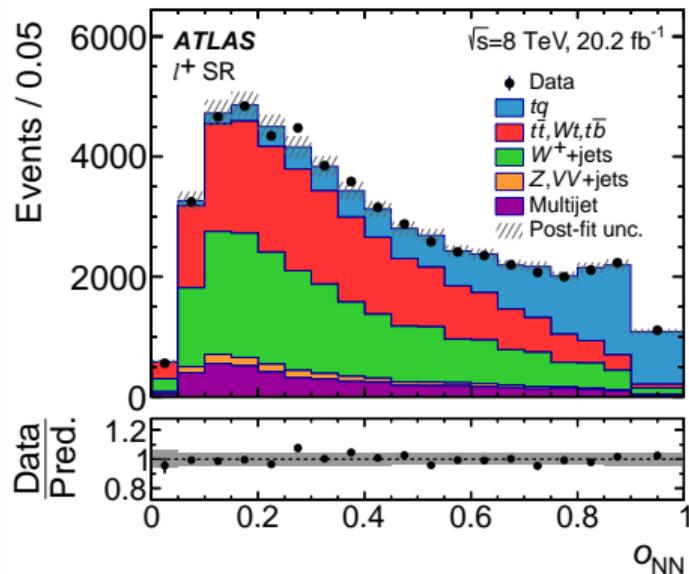
- Measured in fiducial phase space

- In terms of **stable particles**
- $e$  or  $\mu$  ( $p_T > 25$  GeV,  $|\eta| < 2.5$ )
- 2 jets ( $p_T > 30$  GeV,  $|\eta| < 4.5$ ); 1  $b$
- $m(lb) < 160$  GeV

$$\sigma_{tq}^{\text{fid.}} = 9.78 \pm 0.16 \text{ (stat.)} \pm 0.52 \text{ (syst.)} \pm 0.19 \text{ (lumi.) pb (5.8\%)}$$

$$\sigma_{t\bar{q}}^{\text{fid.}} = 5.77 \pm 0.14 \text{ (stat.)} \pm 0.41 \text{ (syst.)} \pm 0.11 \text{ (lumi.) pb (7.8\%)}$$

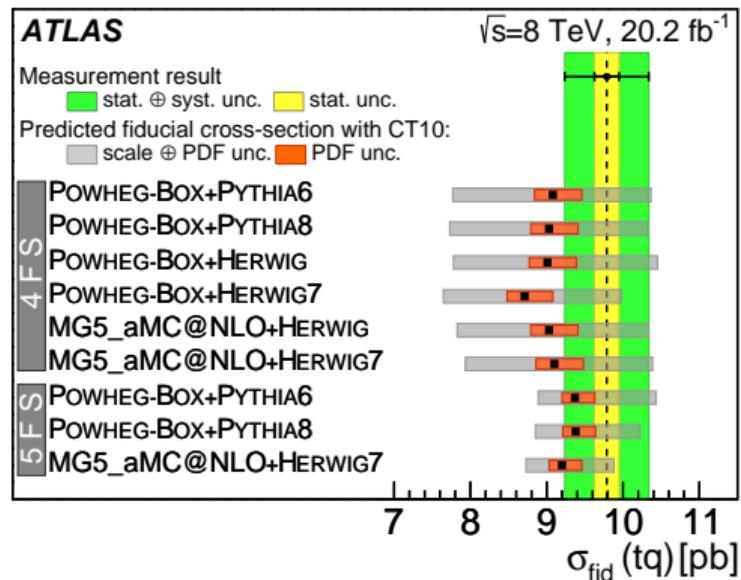




- Measured in fiducial phase space
- Maximum likelihood fit to  $O_{NN}$
- Leading systematics:
  - jet energy scale (3.6%)
  - $\ell$  reconstruction (2.5%)

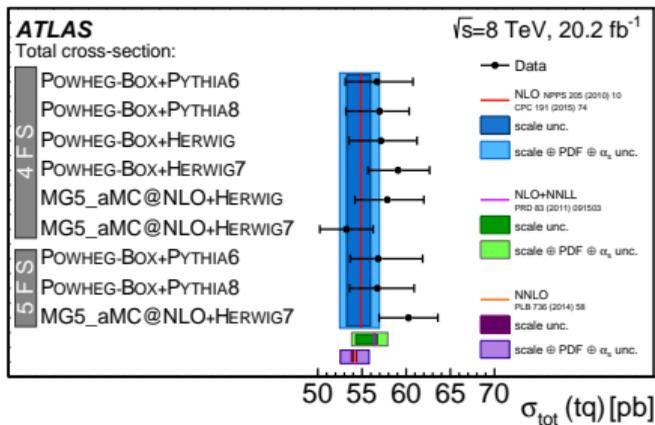
$$\sigma_{tq}^{\text{fid.}} = 9.78 \pm 0.16 \text{ (stat.)} \pm 0.52 \text{ (syst.)} \pm 0.19 \text{ (lumi.) pb (5.8\%)}$$

$$\sigma_{\bar{t}q}^{\text{fid.}} = 5.77 \pm 0.14 \text{ (stat.)} \pm 0.41 \text{ (syst.)} \pm 0.11 \text{ (lumi.) pb (7.8\%)}$$



- Extrapolated into full phase space:

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



- $|V_{tb}|$  without unitarity assumption:

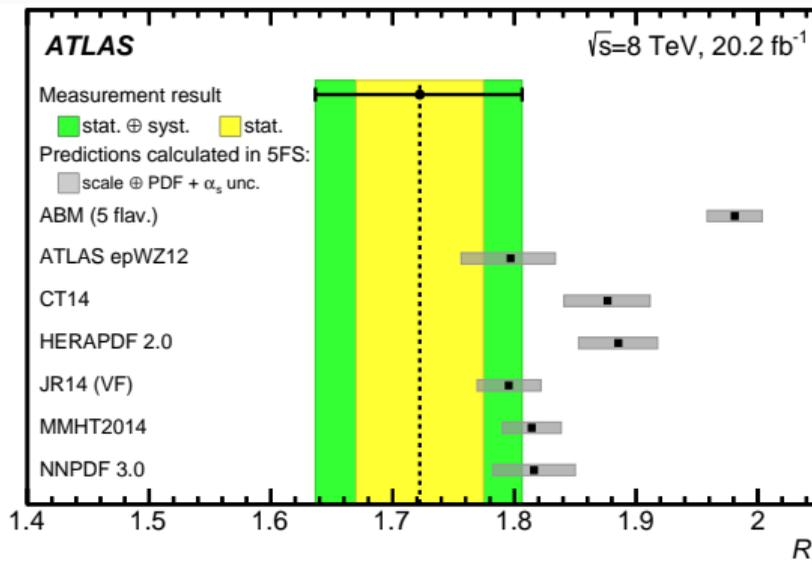
$$|f_{LV} \cdot V_{tb}|^2 = \frac{\sigma_{\text{measured}}}{\sigma_{\text{SM}}}$$

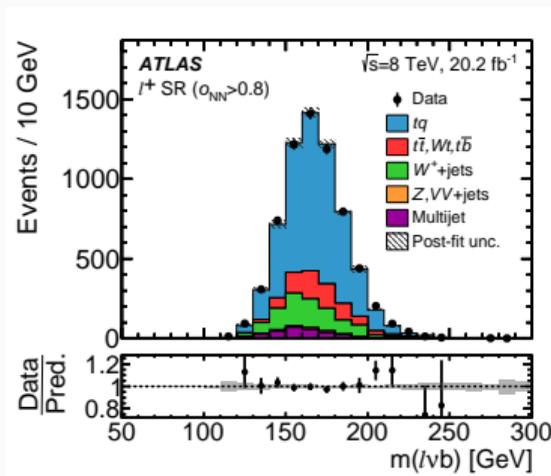
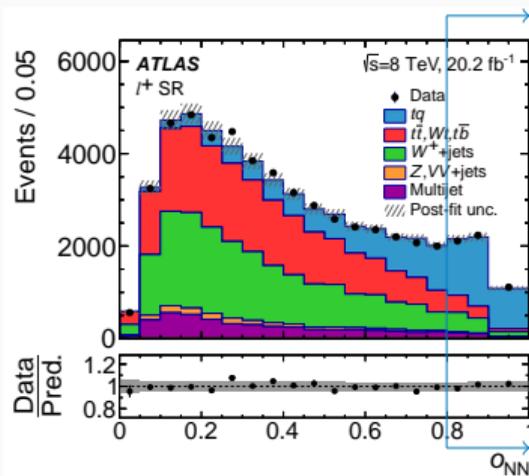
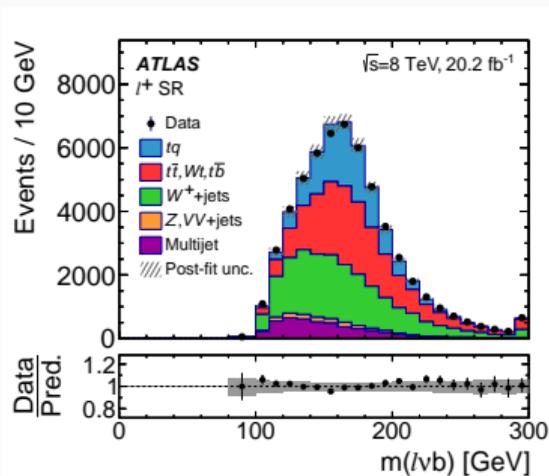
$$\sigma_{tq}^{\text{tot.}} = 56.7^{+4.3}_{-3.8} \text{ pb (7.6\%)}$$

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

$$R_t \equiv \sigma_{tq}/\sigma_{\bar{t}q} = 1.73 \pm 0.05 \text{ (stat.)} \pm 0.07 \text{ (syst.) pb}$$

$$f_{LV} \cdot |V_{tb}| = 1.029 \pm 0.048$$





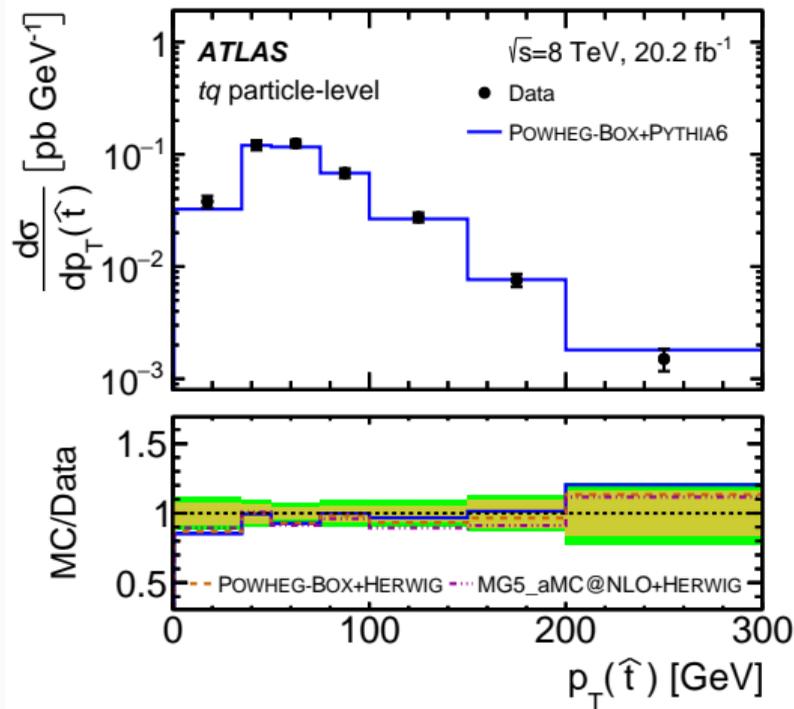
- Cut placed on  $O_{NN} > 0.8$
- Unfolded: parton level, **particle level** (objects defined in terms of **stable particles** in the detector e.g. pseudotop  $\hat{t}$ )
- Leading systematics:
  - jet energy scale
  - modelling of signal and  $t\bar{t}$

$$p_T(\hat{t}) \quad p_T(\hat{j}) \quad p_T(t)$$

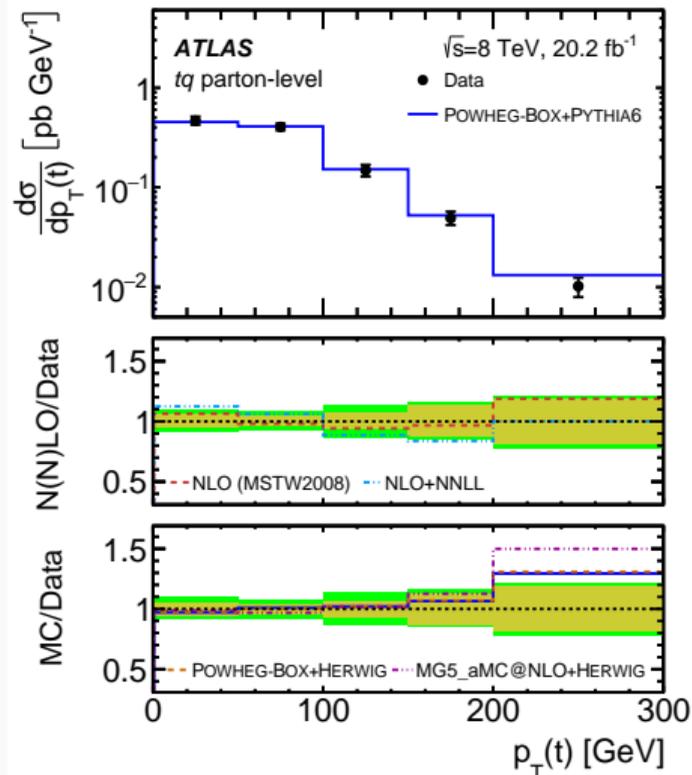
$$|y(\hat{t})| \quad |y(\hat{j})| \quad |y(t)|$$

Separate NN used for  $\hat{j}$  without  $|\eta_j|$

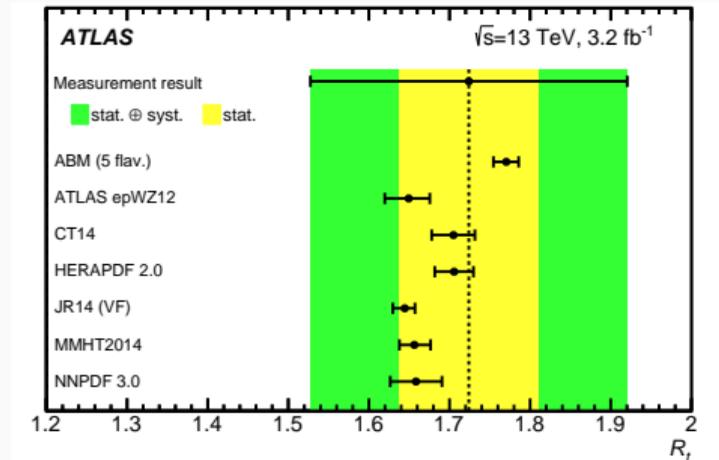
Particle level



Parton level



- Similar strategy to 8 TeV measurement



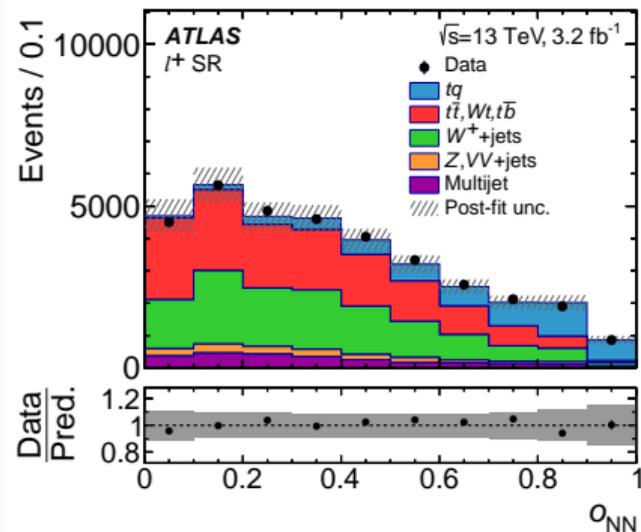
- Leading systematics:
  - parton showering (14%)
  - $b$ -tagging efficiency (7%)
- Systematics are expected to **reduce with more data** and improved predictions

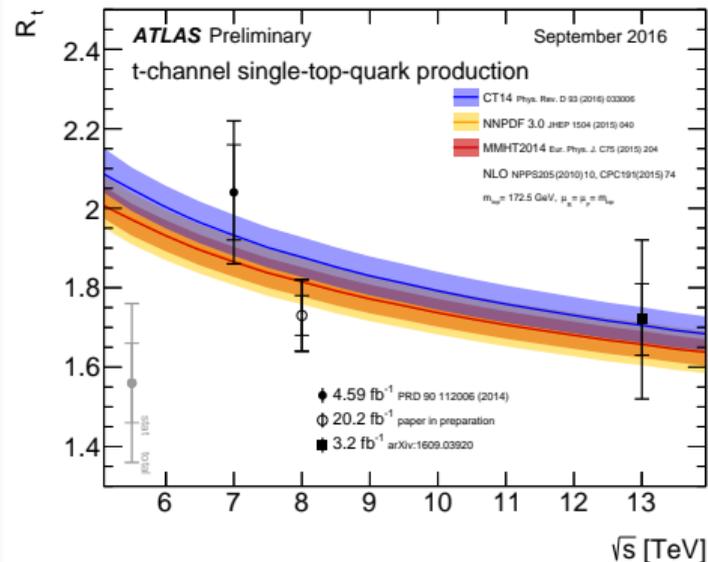
$$\sigma_{tq} = 156 \pm 5 \text{ (stat.)} \pm 27 \text{ (syst.)} \pm 3 \text{ (lumi.) pb (18\%)}$$

$$\sigma_{t\bar{q}} = 91 \pm 4 \text{ (stat.)} \pm 18 \text{ (syst.)} \pm 2 \text{ (lumi.) pb (20\%)}$$

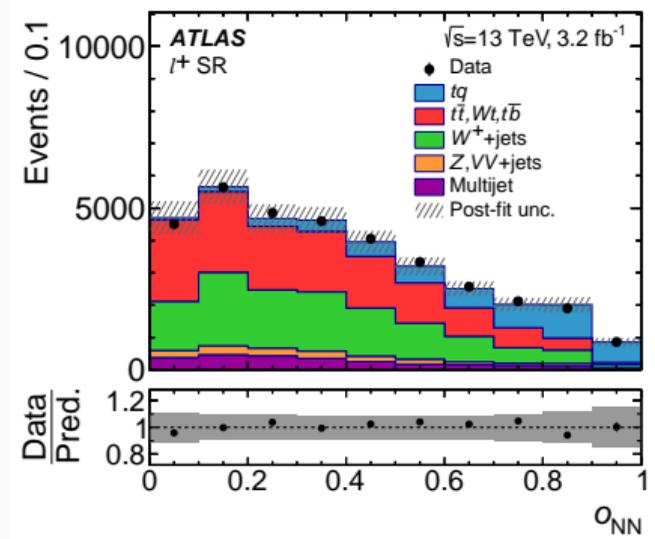
$$R_t = 1.72 \pm 0.09 \text{ (stat.)} \pm 0.18 \text{ (syst.)}$$

$$f_{LV} \cdot |V_{tb}| = 1.07 \pm 0.09$$



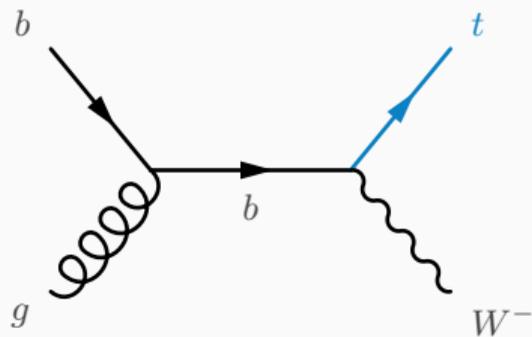


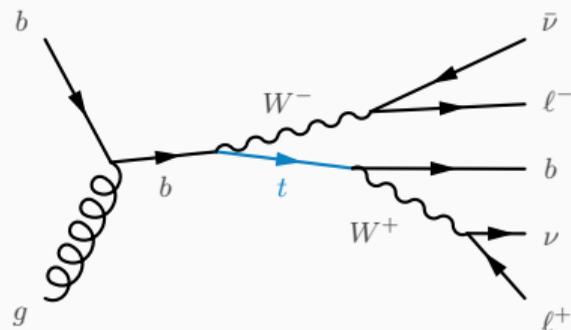
$\sigma_{tq} = 156 \pm 5 \text{ (stat.)} \pm 27 \text{ (syst.)} \pm 3 \text{ (lumi.) pb (18 \%)$   
 $\sigma_{\bar{t}q} = 91 \pm 4 \text{ (stat.)} \pm 18 \text{ (syst.)} \pm 2 \text{ (lumi.) pb (20 \%)$   
 $R_t = 1.72 \pm 0.09 \text{ (stat.)} \pm 0.18 \text{ (syst.)}$   
 $f_{\text{LV}} \cdot |V_{tb}| = 1.07 \pm 0.09$



## $tW$ associated production

---



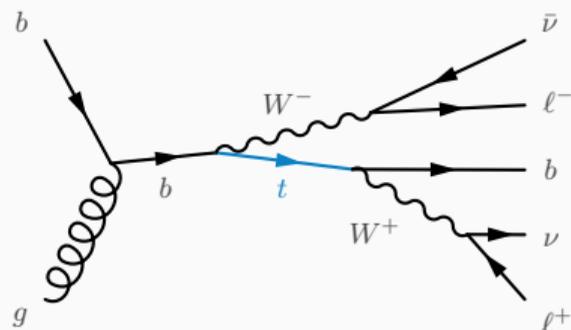


	0j	1j	2j
0b		VR	VR
1b		SR	SR
2b			CR $t\bar{t}$

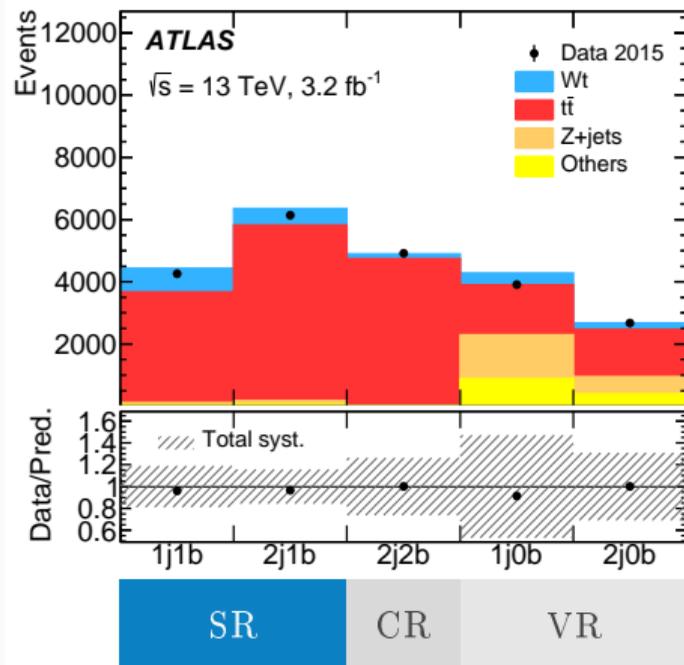
$SR = \text{signal}$ ,  $VR = \text{validation}$ ,  $CR = \text{control}$

- Signature of the dilepton final state:
  - 2 oppositely-charged, isolated leptons
  - $E_T^{\text{miss}}$  from the 2 neutrinos
  - 1 high- $p_T$   $b$ -tagged jet
- Main background:  $t\bar{t}$  (interference at NLO)
- Boosted decision tree to separate  $tW$  from  $t\bar{t}$
- Profile likelihood fit over  $2 \times SR$  and CR

- 2012 dataset:  $20.3 \text{ fb}^{-1}$  at 8 TeV
  - Total  $\sigma_{tW}$  cross-section
  - Fiducial  $\sigma_{tW+t\bar{t}}$
- 2015 dataset:  $3.2 \text{ fb}^{-1}$  at 13 TeV
  - Total  $\sigma_{tW}$  cross-section



- Signature of the dilepton final state:
  - 2 oppositely-charged, isolated leptons
  - $E_T^{\text{miss}}$  from the 2 neutrinos
  - 1 high- $p_T$   $b$ -tagged jet
- Main background:  $t\bar{t}$  (interference at NLO)
- Boosted decision tree to separate  $tW$  from  $t\bar{t}$
- Profile likelihood fit over  $2\times\text{SR}$  and CR



arXiv:1612.07231 ( $tW$  at 13 TeV)

- Separate BDTs trained for the three fit regions

- Most significant BDT inputs:

- $p_T^{\text{sys}}(\ell_1 \ell_2 E_T^{\text{miss}} j_1)$  and
- $m(\ell_1 j_2)$
- $p_T^{\text{sys}}(j_1 j_2)$

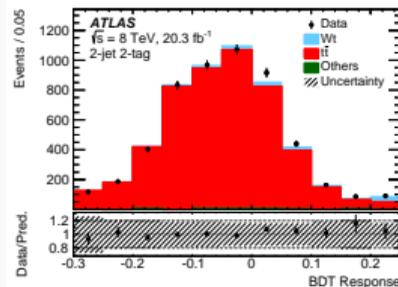
respectively (details)

- Leading systematics:

- $t\bar{t}$  normalisation
- jet reconstruction
- initial/final state radiation

- Statistical uncertainty:  $\sim 6\%$

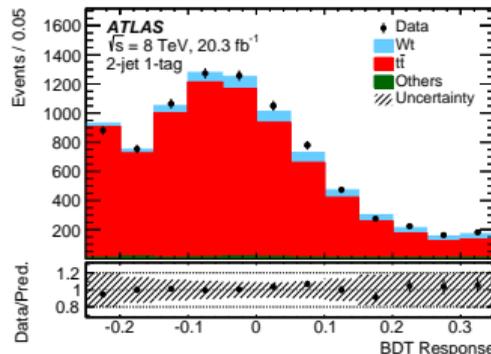
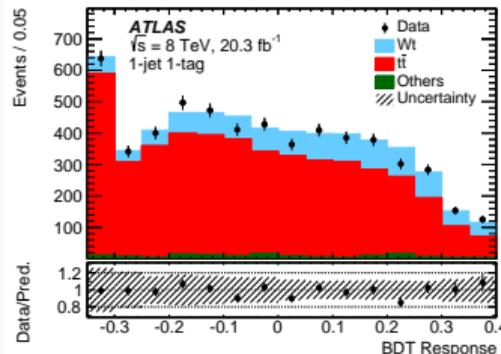
$p_T^{\text{sys}}$  : magnitude of the vectorial  $p_T$  sum



← 2j2b (CR  $t\bar{t}$ )

↓ 1j1b

↓ 2j1b

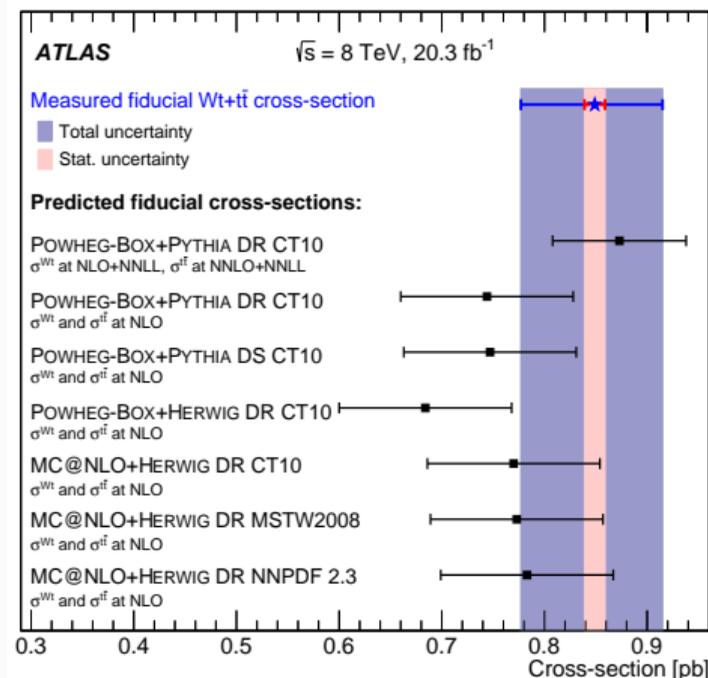


$$\sigma_{tW} = 23.0 \pm 1.3 \text{ (stat.) } {}_{-3.5}^{+3.2} \text{ (syst.) } \pm 1.1 \text{ (lumi.) pb (17\%)}$$

$$|V_{tb}| = 1.01 \pm 0.10$$

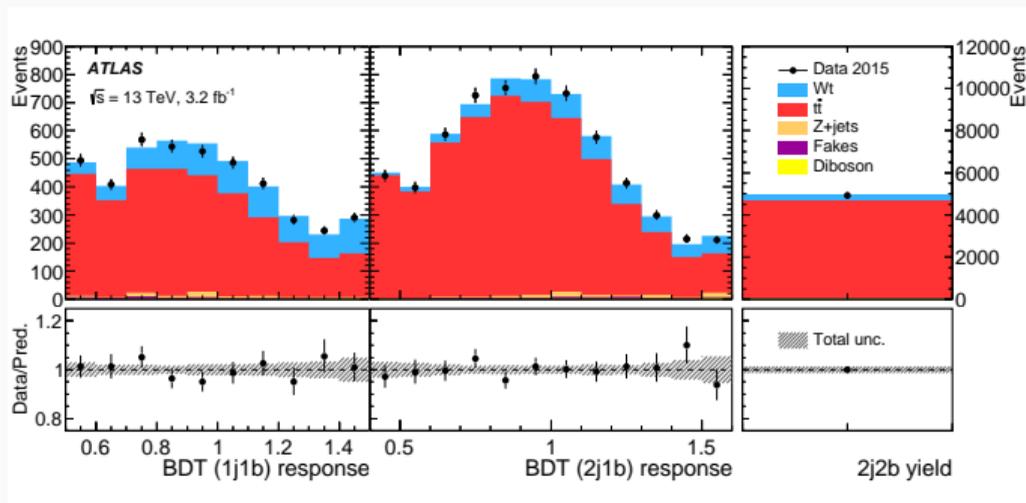
- Fiducial final state also treats  $t\bar{t}$  as signal
- Defined at particle level in terms of stable particles
- Only  $1j1b$  region used in fiducial fit
- Can be compared to  $WWb$  and  $WWbb$  at NLO

$$\sigma_{tW+t\bar{t}} = 0.85 \pm 0.01 \text{ (stat.) } {}^{+0.06}_{-0.07} \text{ (syst.) } \pm 0.03 \text{ (lumi.) pb}$$



- Separate BDTs trained for the two signal regions 1j1b and 2j1b
- Most significant BDT inputs:
  - $p_T^{\text{sys}}(\ell_1 \ell_2 E_T^{\text{miss}} j_1)$  and
  - $p_T^{\text{sys}}(\ell_1 \ell_2)$
 respectively (details)
- Leading systematics:
  - jet energy scale (21%)
  - NLO matrix element (18%)
- Systematics are expected to **reduce with more data** and improved predictions

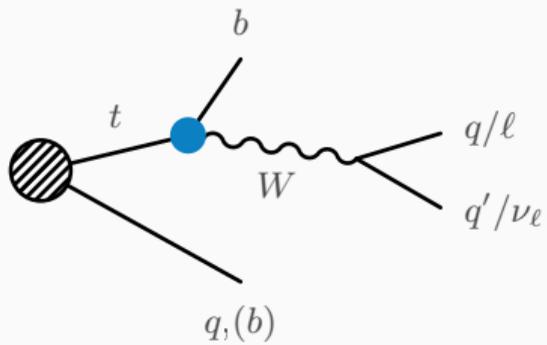
$p_T^{\text{sys}}$ : magnitude of the vectorial  $p_T$  sum



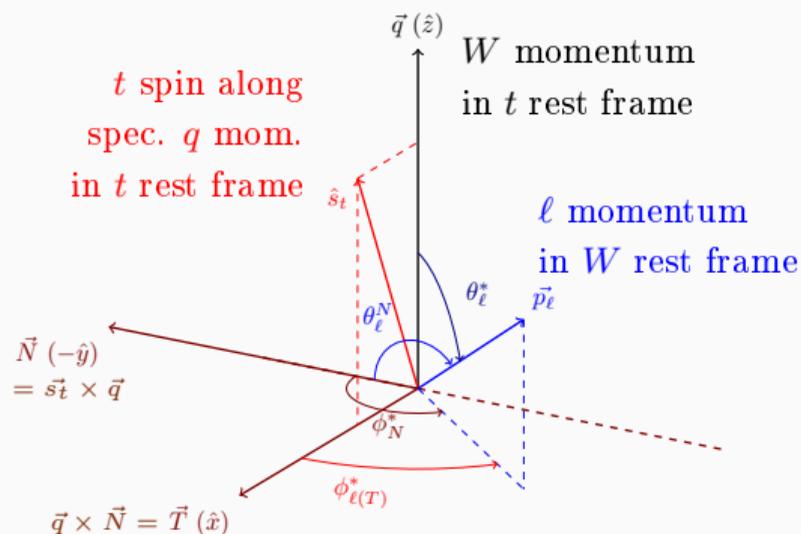
$$\sigma_{tW} = 94 \pm 10 \text{ (stat.) } {}^{+28}_{-22} \text{ (syst.) } \pm 2 \text{ (lumi.) pb (31\%)}$$

## Anomalous couplings ( $t$ -channel)

---



- SM predicts highly polarised top:  
 $P(t) = 0.91$  and  $P(\bar{t}) = -0.86$  (NLO)
- Can be measured using angular asymmetries
- Probe for  $Wtb$  vertex structure

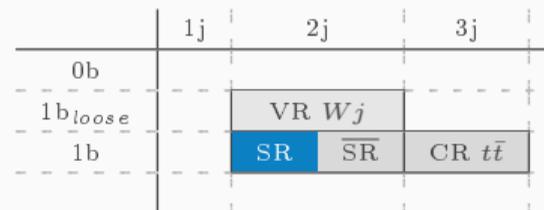


$$A_{\text{FB}} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

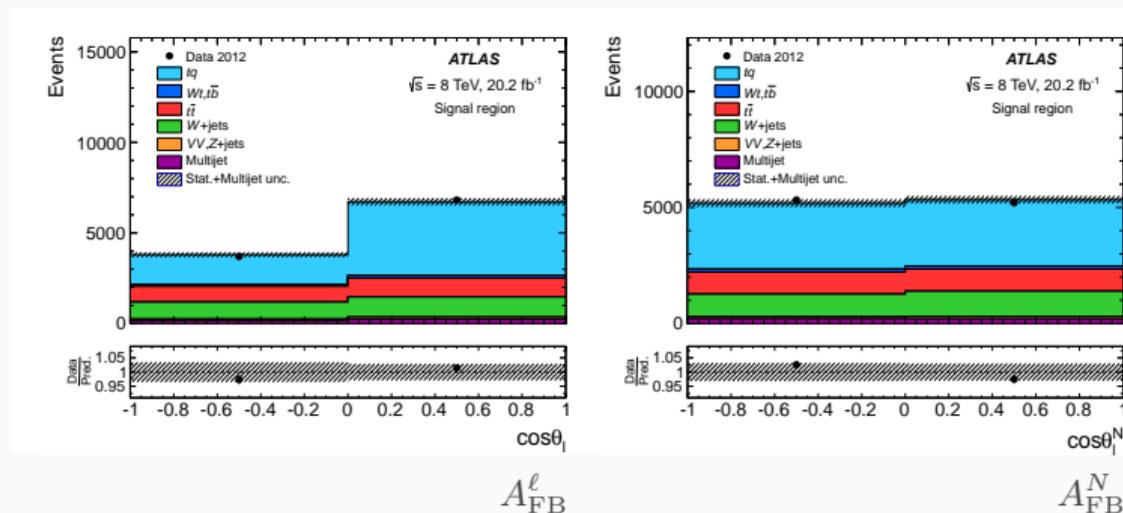
Asymmetry	Angular observable	Polarisation observable	SM prediction
$A_{\text{FB}}^\ell$	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
$A_{\text{FB}}^{tW}$	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P(F_R + F_L)$	0.10
$A_{\text{FB}}$	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3 \rangle = \frac{3}{4}(F_R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

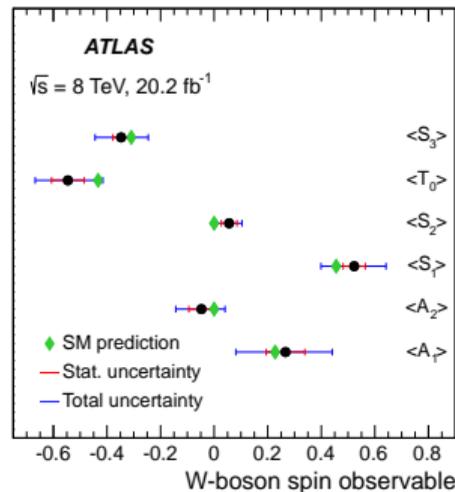
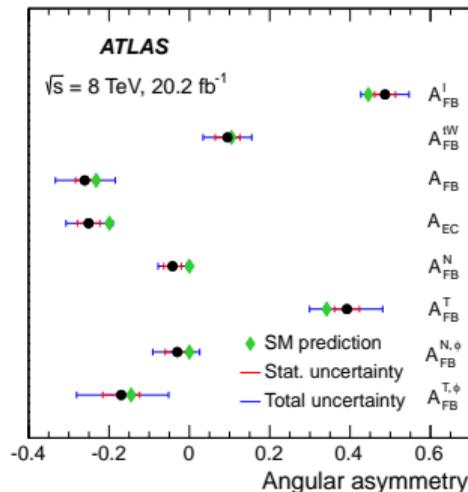
SM predictions at NLO for  $P$  and  $\alpha_\ell$ ;  
NNLO for  $F_{0,L,R}$ ; LO for  $\langle S_{1,2} \rangle$  and  $\langle A_{1,2} \rangle$

- $t$ -channel cuts as before,  
+ cuts for SR vs.  $\overline{\text{SR}}$ :
  - forward  $|\eta_j|$
  - large  $\Delta\eta(b, j)$
  - reco.  $t$  near  $m_{\text{top}}$
  - large scalar sum of  $p_T$
- $\overline{\text{SR}}$  used to constrain  
 $W + \text{jets}$  normalisation
- Maximum likelihood fit  
over SR,  $\overline{\text{SR}}$ , CR  $t\bar{t}$
- Unfolded to parton level
- Leading systematics:
  - $t\bar{t}$  modelling,
  - jet calibration,
  - MC statistics



$SR = \text{signal}$ ,  $VR = \text{validation}$ ,  $CR = \text{control}$





Most general  $Wtb$  interaction in effective operator formalism:

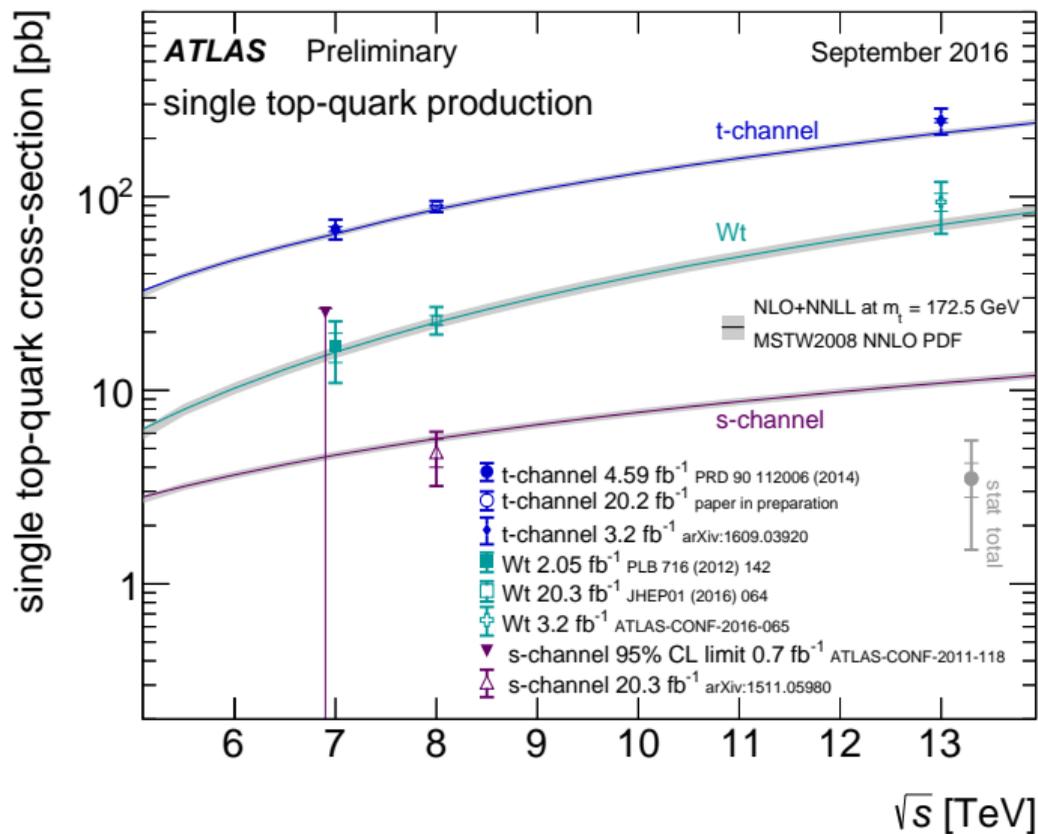
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^-$$

$$- \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{m_W} (g_L P_L + g_R P_R) t W_\mu^-$$

$$+ \text{h.c.}$$

- SM:  $V_L = V_{tb}$ , **anomalous** couplings zero
- If  $g_R$  is complex, the coupling has a **CP-violating** component
- $A_{\text{FB}}^N$  and  $A_{\text{FB}}^\ell$  are used to set a limit on anomalous coupling:  
 $\text{Im } g_R \in [-0.18, 0.06]$  at 95% confidence level (assuming  $V_L = 1$  and  $V_R = g_L = \text{Re } g_R = 0$ )

- Comprehensive 8 TeV results
- New measurements at 13 TeV
- These will be used to tune MC generators and PDFs
- Good agreement with predicted cross-sections
- **More to come** with the full 2015+2016 dataset



Backup

# Systematic ranking: $t$ -channel@8 TeV

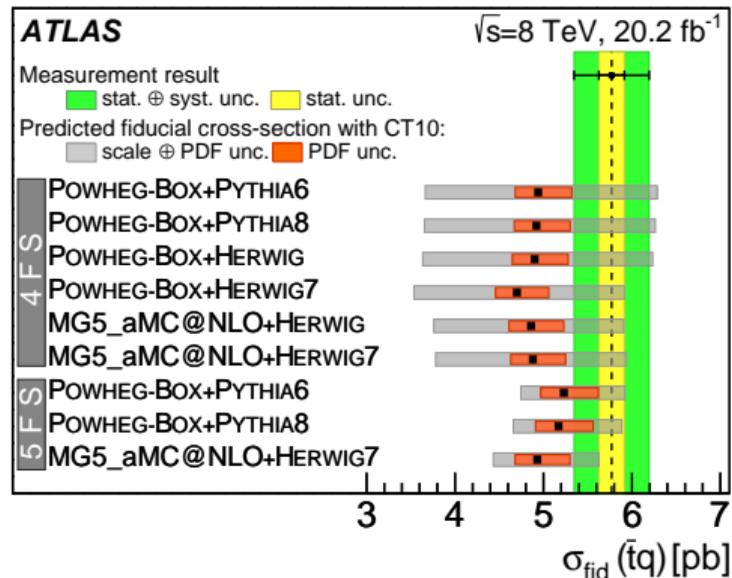
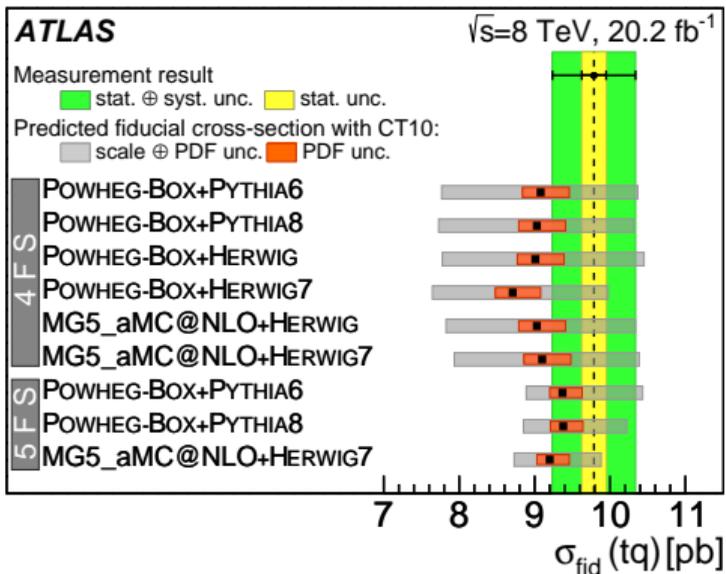
Source	$\Delta\sigma_{\text{fid}}(tq) / \sigma_{\text{fid}}(tq)$ [%]	$\Delta\sigma_{\text{fid}}(\bar{t}q) / \sigma_{\text{fid}}(\bar{t}q)$ [%]
Data statistics	$\pm 1.7$	$\pm 2.5$
Monte Carlo statistics	$\pm 1.0$	$\pm 1.4$
Background normalisation	$< 0.5$	$< 0.5$
Background modelling	$\pm 1.0$	$\pm 1.6$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

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

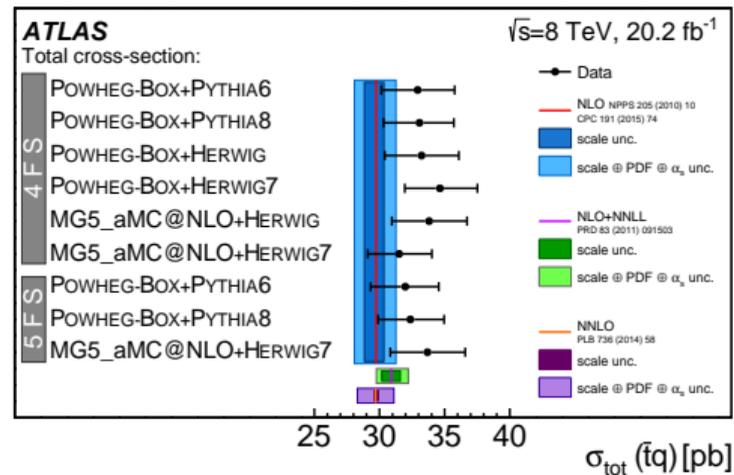
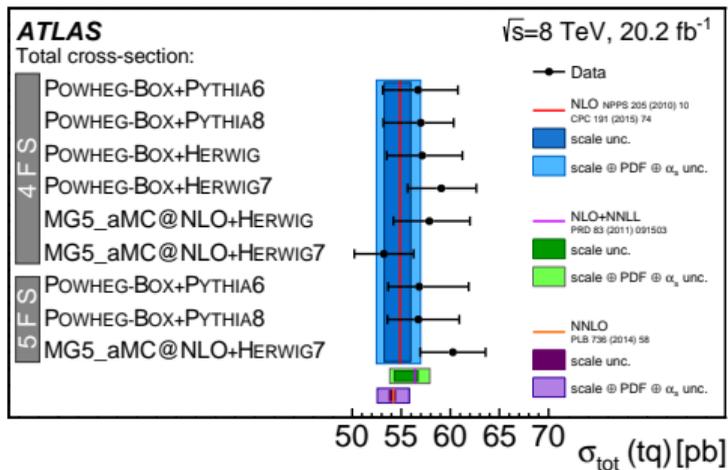
$$A_{\text{fid.}} = \frac{N_{\text{fiducial}}}{N_{\text{total}}} \quad \sigma_{\text{fid.}} = \frac{N_{\text{fiducial}}}{N_{\text{selected}}} \cdot \frac{\hat{\nu}}{\mathcal{L}}$$

- $\hat{\nu}$  is the measured expectation value of the number of signal events
- 
- Fiducial phase space: apply event selection at **generator level**
  - Stable particles (lifetime in MC event record greater than  $3 \times 10^{-11}$  s):
    - $e, \mu, \nu$  defined to be decay products of  $W$  (incl. via  $\tau$ )  
(implicit  $W$ -boson match excludes hadronic decay products)
    - $\ell$  **momentum** includes photons in a cone of radius  $\Delta R = 0.1$
    - anti- $k_t$  **jets** ( $R = 0.4$ ) using all stable particles except the  $\ell$  and photons used above
    - $b$ -**jets** are jets with  $|\eta| < 2.5$  and ghost-matched to a  $b$  hadron
    - **overlap removal** rejects events where  $\ell$  is in a jet cone of  $\Delta R = 0.4$
    - $m(\ell b) < 160$  GeV
  - The **pseudo-top** ( $\hat{t}$ ) is constructed from  $p_W + p_b$  at particle level
  - The  $W$  is in turn constructed from  $p_\ell + p_\nu$  using a  $m_W$  constraint

# Fiducial cross-section: $t$ -channel@8 TeV



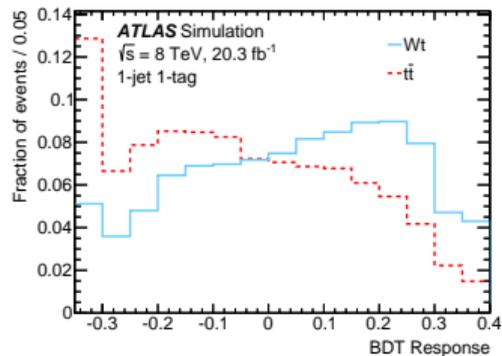
# Total cross-section: $t$ -channel@8 TeV



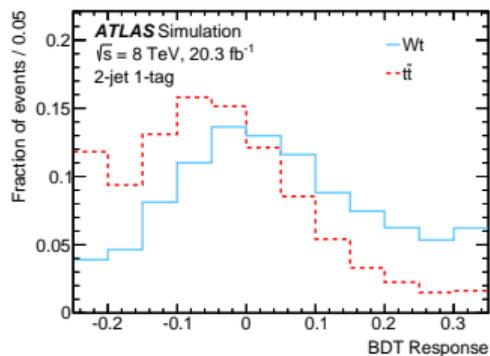
# Systematics ranking: $t$ -channel@13 TeV

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

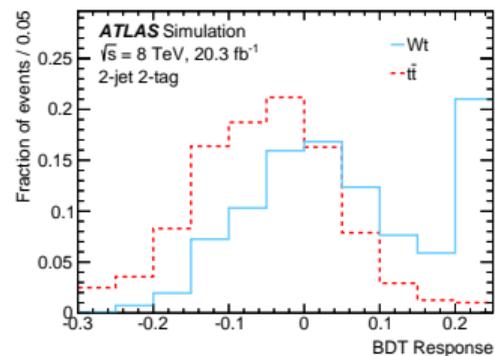
# Post-fit BDT distributions: $tW@8\text{ TeV}$



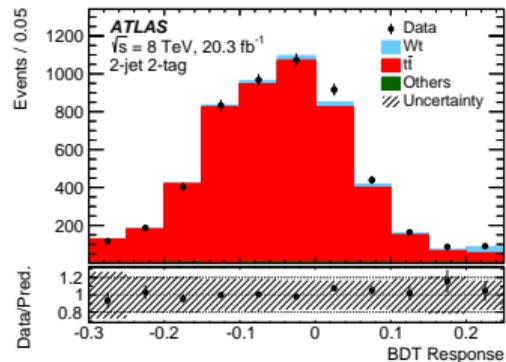
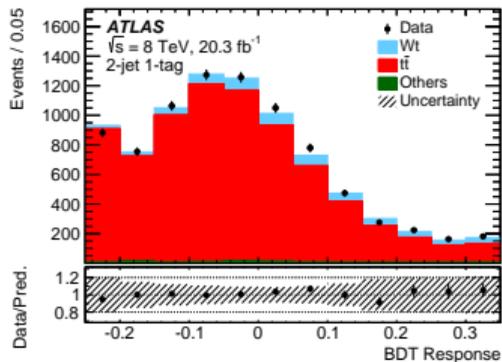
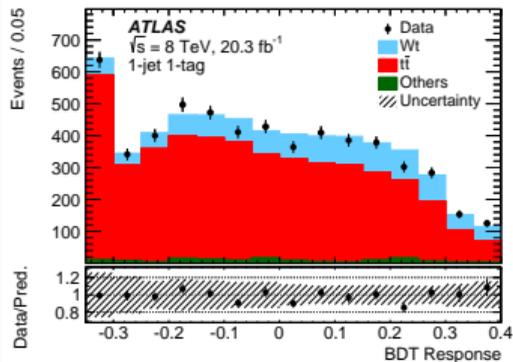
1j1b



2j1b



2j2b

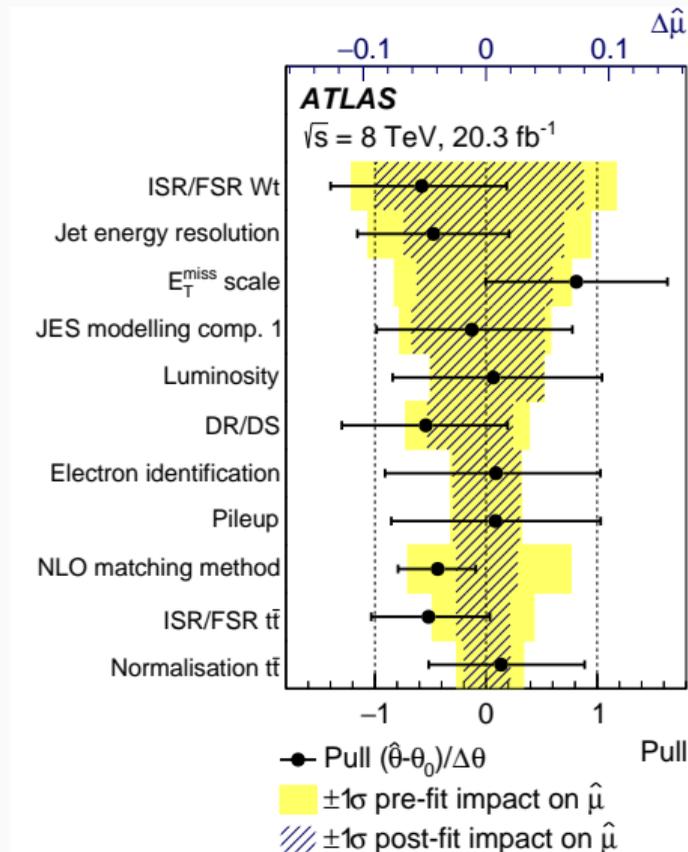


# Input significance: $tW@8\text{ TeV}$

Variable	1-jet, 1-tag	2-jet 1-tag	2-jet 2-tag	$\Delta R (\ell_2, j_2)$			
$p_T^{\text{sys}} (\ell_1, \ell_2, E_T^{\text{miss}}, j_1)$	1			$\Delta R (\ell_2, j_1)$			6
$p_T^{\text{sys}} (\ell_1, \ell_2, j_1)$	7			$\Delta R (\ell_1, \ell_2)$			11
$p_T^{\text{sys}} (\ell_1, \ell_2)$	13			$\Delta R ((\ell_1, \ell_2), j_2)$			14
$p_T^{\text{sys}} (j_1, j_2)$		10	1	$m (\ell_2, j_1)$	10		9
$p_T^{\text{sys}} (\ell_1, \ell_2, E_T^{\text{miss}})$		12	2	$m (\ell_1, j_2)$			3
$p_T^{\text{sys}} (\ell_1, \ell_2, E_T^{\text{miss}}, j_1, j_2)$		13		$m (j_1, j_2)$			1
$p_T^{\text{sys}} (\ell_1, j_1)$			13	$m (\ell_2, j_2)$			2
$\sigma(p_T^{\text{sys}}) (\ell_1, \ell_2, E_T^{\text{miss}}, j_1)$	4	5		$m (\ell_1, j_1)$			7
$p_T (j_2)$			8	$m (\ell_1, \ell_2)$			8
$\Delta p_T (\ell_1, \ell_2)$	8			$m (\ell_2, j_1, j_2)$			15
$\Delta p_T ((\ell_1, \ell_2, j_1), (E_T^{\text{miss}}))$	9			$m (\ell_1, \ell_2, j_1, j_2)$			11
$\Delta p_T (E_T^{\text{miss}}, j_1)$		9		$m_T (j_1, E_T^{\text{miss}})$		5	15
$\Delta p_T (\ell_1, \ell_2, E_T^{\text{miss}}, j_1)$		16		$m_{T2}$	11		
$\Delta p_T (\ell_2, j_2)$			14	$E/m (\ell_1, \ell_2, j_2)$			16
$\Delta R (\ell_1, j_1)$	2		5	$\sum E_T$	3		
$\Delta R (\ell_2, j_1)$		4	10	Centrality( $\ell_1, \ell_2$ )	6		
$\Delta R (\ell_2, j_2)$		6		Centrality( $\ell_1, j_1$ )	12		
$\Delta R (\ell_2, j_1)$		11		Centrality( $\ell_2, j_2$ )			12

# Systematics: $tW@8$ TeV

Uncertainty	Impact on $\hat{\mu}$ [%]
Statistical	$\pm 5.8$
Luminosity	$\pm 4.7$
Theory modelling	
ISR/FSR	+8.2 -9.4
Hadronisation	$\pm 1.7$
NLO matching method	$\pm 2.5$
PDF	$\pm 0.6$
DR/DS	+2.2 -4.8
Detector	
Jet	+9.0 -9.9
Lepton	$\pm 3.0$
$E_T^{\text{miss}}$	$\pm 5.5$
<b><math>b</math>-tag</b>	$\pm 1.0$
Background norm.	+10 -8.5
<b>Total</b>	+16 -17



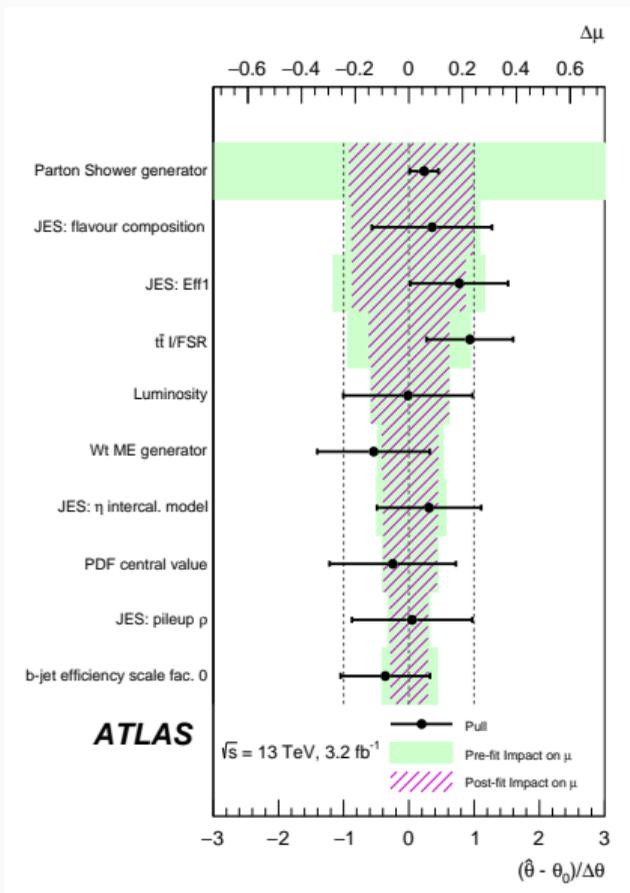
---

At least one jet with  $p_T > 25$  GeV,  $|\eta| < 2.5$   
 Exactly two leptons of opposite charge with  $p_T > 20$  GeV,  
 $|\eta| < 2.5$  for muons and  $|\eta| < 2.47$  excluding  $1.37 < |\eta| < 1.52$  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	$E_T^{\text{miss}} > 50$ GeV,      if $M_{\ell\ell} < 80$ GeV $E_T^{\text{miss}} > 20$ GeV,      if $M_{\ell\ell} > 80$ GeV	
Same flavour	$E_T^{\text{miss}} > 40$ GeV,      always veto,      if $M_{\ell\ell} < 40$ GeV $4E_T^{\text{miss}} > 5M_{\ell\ell}$ ,      if $40$ GeV $< M_{\ell\ell} < 81$ GeV veto,      if $81$ GeV $< M_{\ell\ell} < 101$ GeV $2M_{\ell\ell} + E_T^{\text{miss}} > 300$ GeV,      if $M_{\ell\ell} > 101$ GeV	

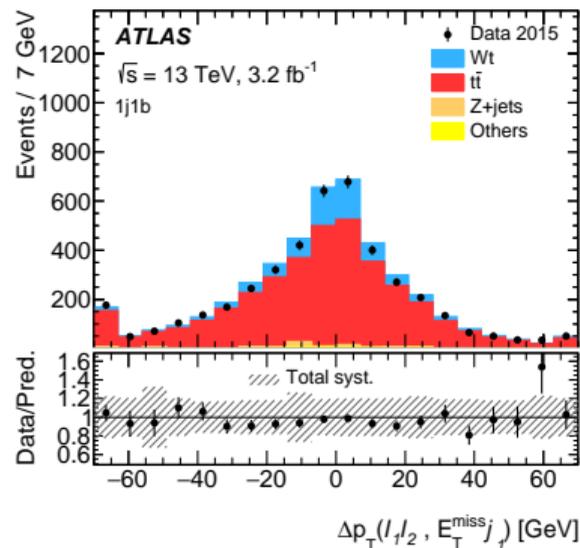
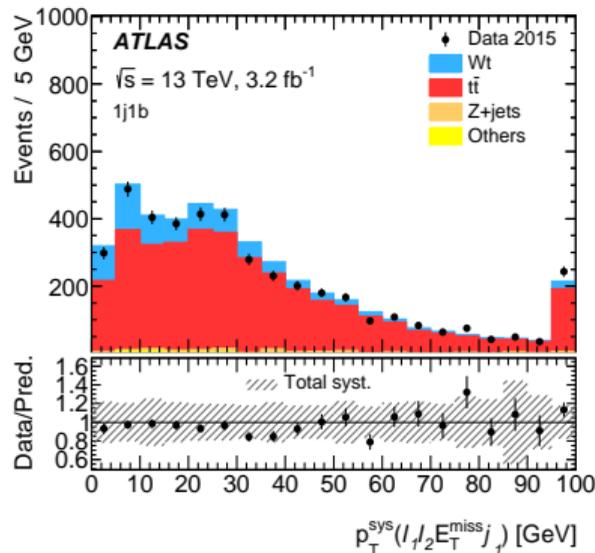
---



Source	$\Delta\sigma_{Wt}/\sigma_{Wt}[\%]$
Jet energy scale	21
Jet energy resolution	8.6
$E_T^{\text{miss}}$ 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

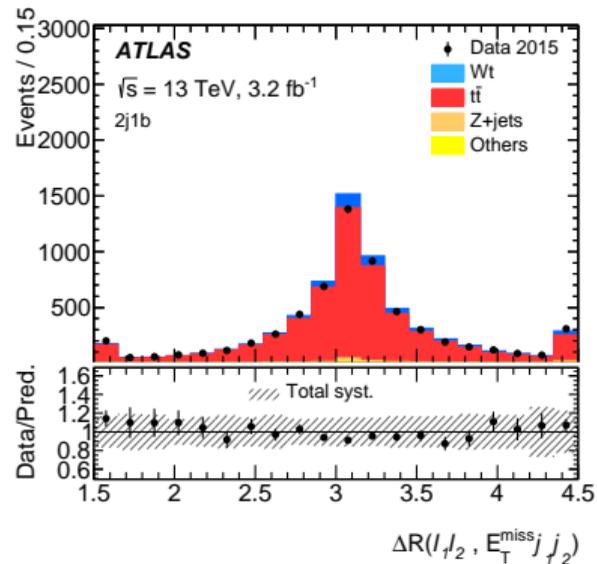
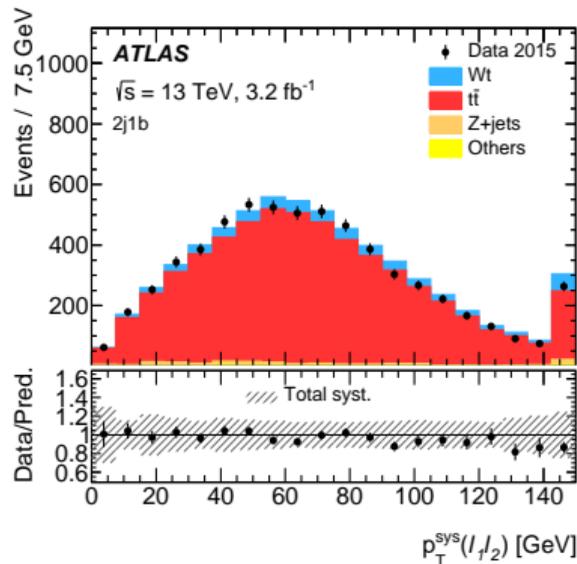
# BDT input significance: $tW@13\text{ TeV}$

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



# BDT input significance: $tW@13\text{ TeV}$

Variable	$S [10^{-2}]$
2j1b	
$p_T^{\text{sys}}(\ell_1\ell_2)$	1.7
$\Delta R(\ell_1\ell_2, E_T^{\text{miss}} j_1j_2)$	1.7
$\Delta R(\ell_1\ell_2, j_1j_2)$	1.5
$m(\ell_1j_2)$	1.4
$\Delta p_T(\ell_1\ell_2, E_T^{\text{miss}})$	1.4
$\Delta p_T(\ell_1, j_1)$	1.4
$m(\ell_1j_1)$	1.3
$p_T(\ell_1)$	1.3
$\sigma(p_T^{\text{sys}})(\ell_1\ell_2 E_T^{\text{miss}} j_1)$	1.2
$\Delta R(\ell_1, j_1)$	1.2
$p_T(j_2)$	0.9
$\sigma(p_T^{\text{sys}})(\ell_1\ell_2 E_T^{\text{miss}} j_1j_2)$	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



# Systematics: anomalous coupling @8 TeV

Uncertainty source	$\Delta A_{\text{FB}}^{\ell} \times 10^2$	$\Delta A_{\text{FB}}^{tW} \times 10^2$	$\Delta A_{\text{FB}} \times 10^2$	$\Delta A_{\text{EC}} \times 10^2$	$\Delta A_{\text{FB}}^N \times 10^2$	$\Delta A_{\text{FB}}^T \times 10^2$	$\Delta A_{\text{FB}}^{N,\phi} \times 10^2$	$\Delta A_{\text{FB}}^{T,\phi} \times 10^2$
Statistical uncertainty	$\pm 2.6$	$\pm 3.1$	$\pm 2.3$	$\pm 2.8$	$\pm 2.2$	$\pm 3.1$	$\pm 3.0$	$\pm 4.6$
Simulation statistics	$\pm 1.7$	$\pm 1.9$	$\pm 1.4$	$\pm 1.7$	$\pm 1.3$	$\pm 2.0$	$\pm 1.8$	$\pm 2.9$
Luminosity	$< 0.1$	$< 0.1$	$< 0.1$	$< 0.1$	$< 0.1$	$< 0.1$	$< 0.1$	$< 0.1$
Background normalisation	$\pm 0.5$	$\pm 0.5$	$\pm 0.9$	$\pm 0.7$	$\pm 0.4$	$\pm 1.1$	$\pm 0.6$	$\pm 1.1$
$E_{\text{T}}^{\text{miss}}$ reconstruction	+0.9 -0.1	+0.4 -0.7	+1.1 -0.7	+0.8 -0.2	+0.3 -0.4	+0.5 -0.3	+0.5 -0.8	+0.4 -1.3
Lepton reconstruction	+1.0 -0.4	+0.1 -1.3	$\pm 1.4$	+0.6 -0.3	+0.1 -0.2	+1.3 -1.5	+0.6 -0.5	+1.6 -0.6
Jet reconstruction	$\pm 2.1$	$\pm 2.5$	$\pm 1.2$	$\pm 1.8$	$\pm 0.8$	$\pm 0.5$	$\pm 1.6$	$\pm 1.3$
Jet energy scale	+1.3 -1.2	+2.0 -1.6	+3.4 -2.7	+2.0 -0.7	+0.9 -0.8	+3.9 -4.6	+0.6 -2.5	+4.5 -2.5
Jet flavour tagging	$\pm 0.9$	$\pm 0.3$	$\pm 0.6$	$\pm 0.4$	$\pm 0.2$	$\pm 0.6$	$\pm 0.3$	$\pm 0.6$
PDF	$\pm 0.2$	$< 0.1$	$< 0.1$	$\pm 0.2$	$\pm 0.1$	$\pm 0.1$	$\pm 0.1$	$\pm 0.4$
$t\bar{t}$ generator	$\pm 2.3$	$\pm 1.0$	$\pm 0.2$	$\pm 1.2$	$\pm 0.2$	$\pm 3.5$	$\pm 1.7$	$\pm 1.3$
$t\bar{t}$ parton shower	$\pm 0.6$	$\pm 0.5$	$\pm 2.7$	$\pm 0.3$	$\pm 1.5$	$\pm 1.0$	$\pm 0.9$	$\pm 1.6$
$t\bar{t}$ scales	$\pm 0.2$	$\pm 0.4$	$\pm 1.2$	$\pm 0.3$	$\pm 0.3$	$\pm 0.8$	$\pm 0.3$	$\pm 1.3$
$Wt$ , $s$ -channel generator	$\pm 1.0$	$\pm 1.1$	$\pm 0.4$	$\pm 0.3$	$\pm 0.2$	$\pm 0.8$	$\pm 0.3$	$\pm 1.4$
$Wt$ , $s$ -channel scales	$\pm 0.9$	$\pm 0.3$	$\pm 0.3$	$\pm 0.3$	$\pm 0.6$	$\pm 0.5$	$\pm 0.4$	$\pm 0.9$
$t$ -channel NLO generator	$\pm 1.4$	$\pm 0.6$	$\pm 0.6$	$\pm 2.7$	$\pm 0.3$	$\pm 4.5$	$\pm 2.6$	$\pm 7.2$
$t$ -channel LO–NLO generator	$\pm 1.5$	$\pm 2.0$	$\pm 2.6$	$\pm 1.8$	$\pm 0.5$	$\pm 1.9$	$\pm 1.3$	$\pm 3.2$
$t$ -channel parton shower	$\pm 0.5$	$\pm 1.0$	$\pm 3.5$	$\pm 0.2$	$\pm 0.7$	$\pm 0.9$	$< 0.1$	$\pm 1.1$
$t$ -channel scales	$\pm 1.1$	$\pm 2.0$	$\pm 0.6$	$\pm 1.6$	$\pm 0.9$	$\pm 2.2$	$\pm 1.4$	$\pm 2.6$
$W$ +jets, multijet modelling	+1.9 -2.4	+0.9 -1.0	+2.2 -2.1	+1.3 -1.2	+0.7 -0.6	+1.3 -1.7	$\pm 0.6$	+2.3 -1.7
Total systematic uncertainty	+5.4 -5.4	+5.2 -5.3	+7.3 -6.9	+5.3 -4.8	+2.9 -2.9	+8.3 -8.8	+4.8 -5.4	+10.9 -10.1

## Angular distributions: anomalous coupling @8 TeV

Angular distribution of any  $t$  decay product  $X$  in the  $t$  rest frame:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d(\cos \theta_X)} = \frac{1}{2} (1 + \alpha_X P \cos \theta_X)$$

Lepton spin analysing power  $\alpha_\ell = \pm 0.998$  at NLO.  $P(t) = 0.91$  and  $P(\bar{t}) = -0.96$  at NLO.

Observed:  $\alpha_\ell P = 0.97 \pm 0.05$  (stat.)  $\pm 0.11$  (syst.) (12%)

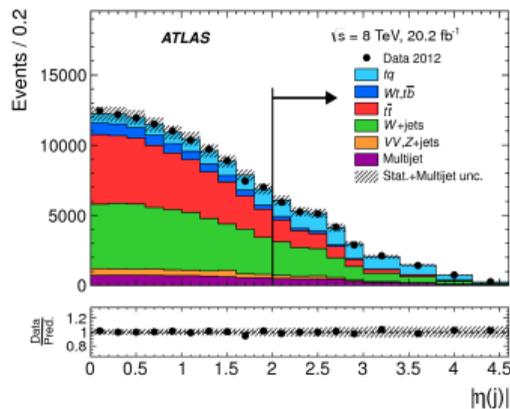
---

Parametrisation of the spin-density matrix elements for the  $W$  boson helicity components  $0, \pm 1$ :

$$\frac{1}{\Gamma} \frac{d\Gamma}{d(\cos \theta_\ell^*) d\phi_\ell^*} = \frac{3}{8\pi} \left\{ \frac{2}{3} + \frac{1}{\sqrt{6}} \langle T_0 \rangle (3 \cos^2 \theta_\ell^* - 1) + \langle S_3 \rangle \cos \theta_\ell^* + \langle S_1 \rangle \cos \phi_\ell^* \sin \theta_\ell^* \right. \\ \left. + \langle S_2 \rangle \sin \phi_\ell^* \sin \theta_\ell^* - \langle A_1 \rangle \cos \phi_\ell^* \sin 2\theta_\ell^* - \langle A_2 \rangle \sin \phi_\ell^* \sin 2\theta_\ell^* \right\}$$

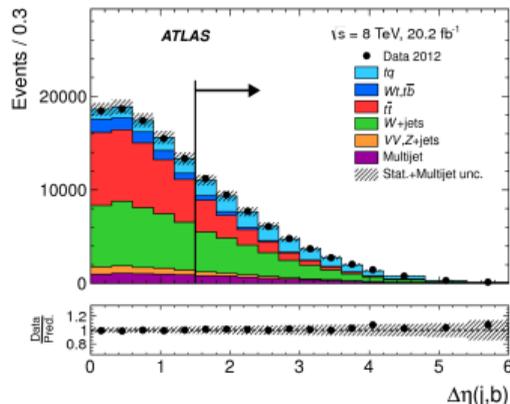
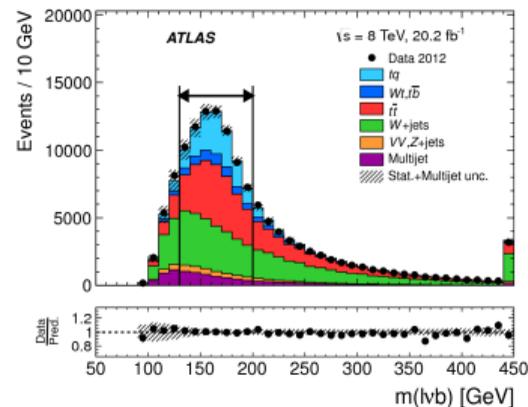
- $\theta_\ell^*$  and  $\phi_\ell^*$  are the angles of the  $\ell$  momentum in the  $W$  rest frame
- The spin observables  $\langle S_{1,2} \rangle$  and  $\langle A_{1,2} \rangle$  are proportional to the top polarisation  $P$
- $\langle T_0 \rangle$  and  $\langle S_3 \rangle$  are independent of  $P$  but are related to the  $W$  helicity fractions  $F_{R,L,0}$

# Signal region cuts: anomalous coupling @8 TeV



← spectator  $q$  (jet) tends to be forward for  $t$ -channel

reject events involving non- $t$  processes by reco.  $t$  mass →



←  $\eta$ -separation of jets  $> 1.5$  to reduce  $t\bar{t}$  background

Scalar sum of  $p_T$  above 195 GeV to reduce bkgd.s, largely  $W + jets$  →

