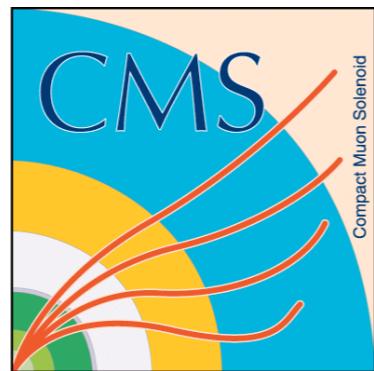


Recent results in single top production at the LHC

9th Large Hadron Collider Physics Conference
7-12th June 2021

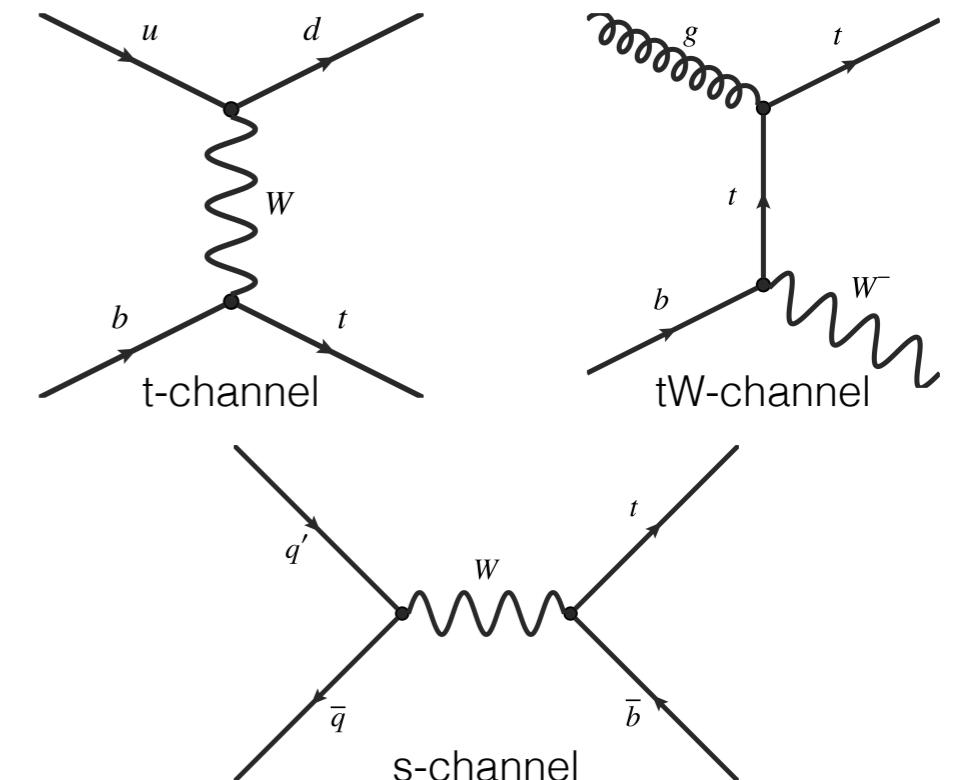
Galo Gonzalvo Rodríguez
On behalf of the ATLAS and CMS collaborations
07-06-2021

Instituto de Física Corpuscular (IFIC) - CSIC/UV

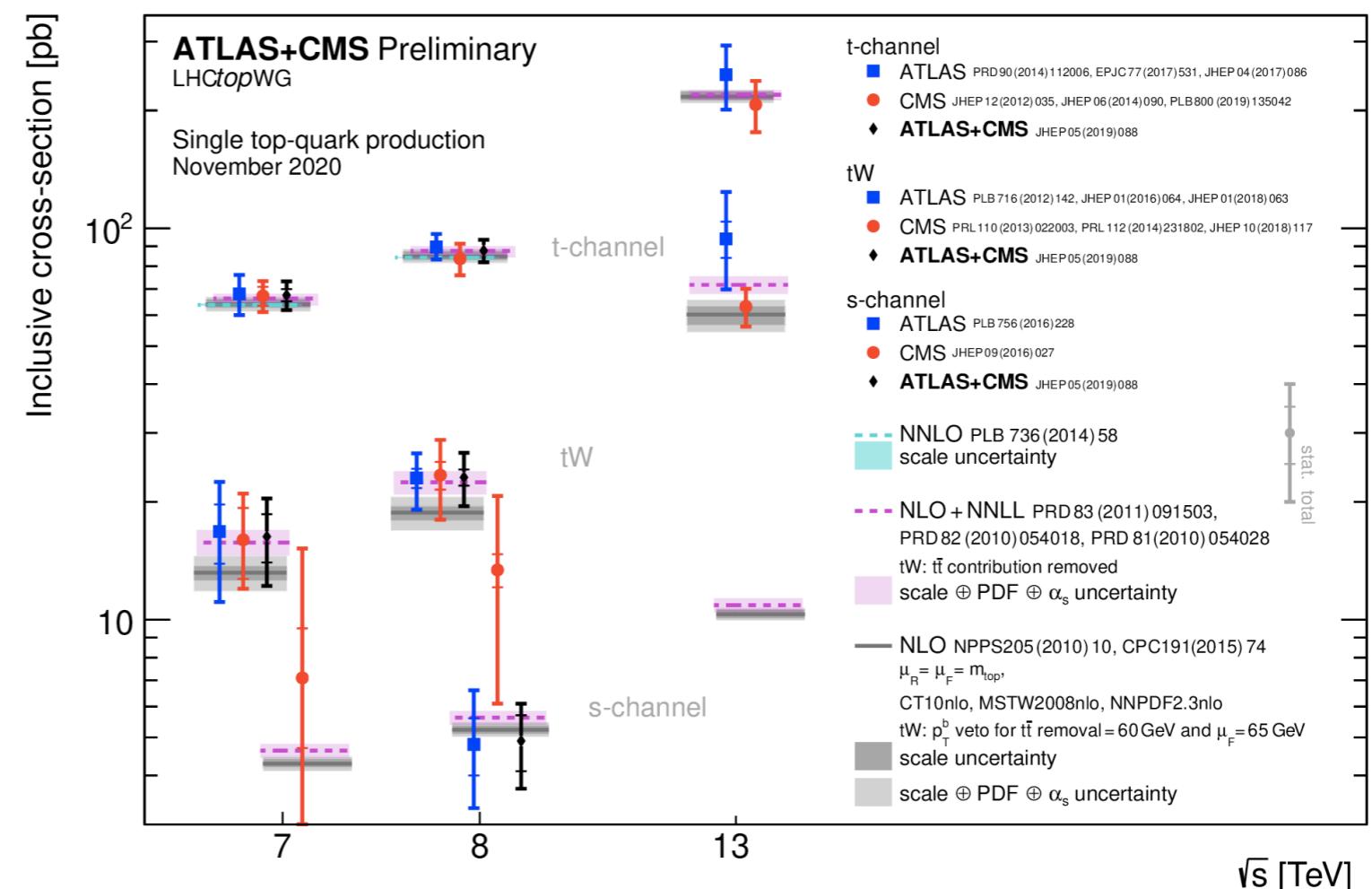


OVERVIEW

- Single-top-quark production is mediated by the EW interaction.
- The tWb vertex is involved in the production and decay of the top quarks.
- Three contributing processes at LO: t-channel, W boson production in association with a top quark (tW) and s-channel.
- At NLO other rare production modes can be studied: tZq , tHq , $t\gamma q$, tWZ .



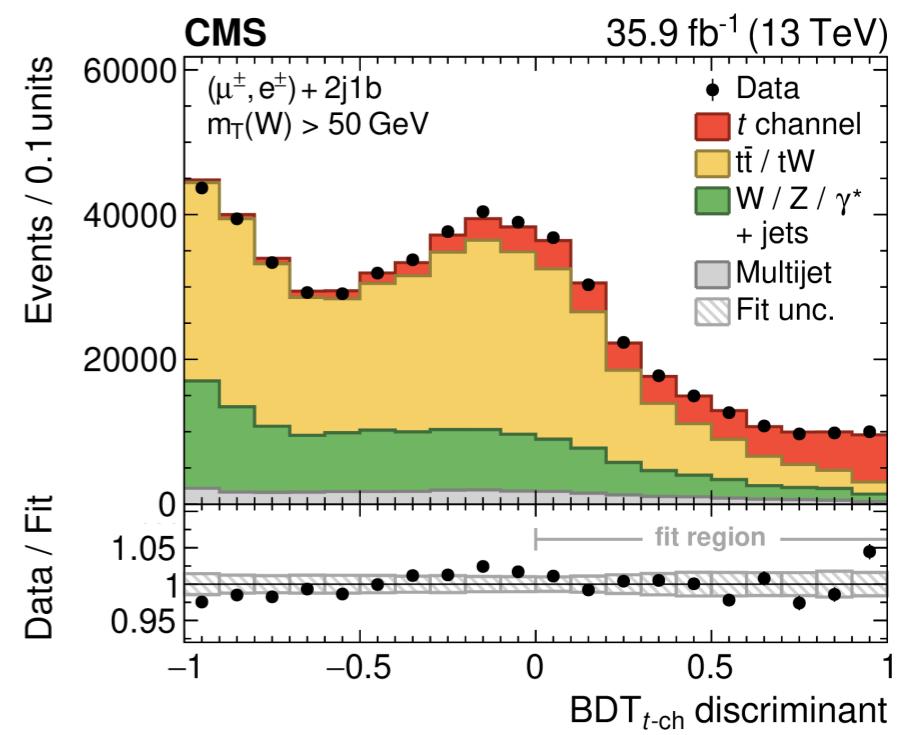
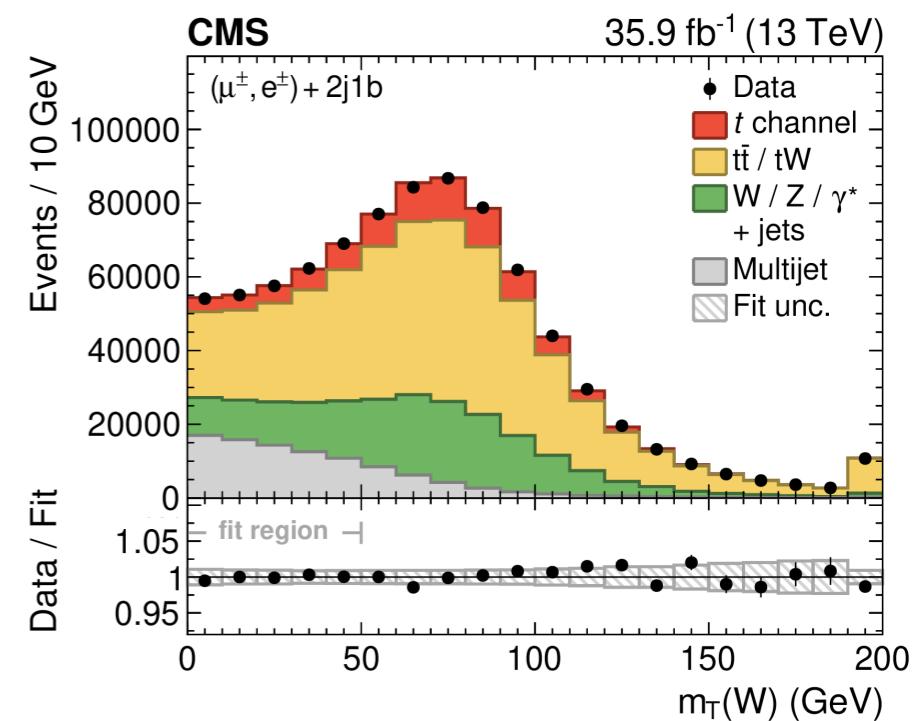
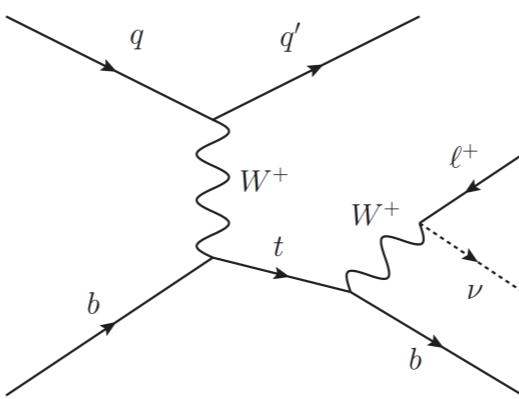
- Results covered in this talk:
 - t-channel: Differential measurements and top-quark polarisation.
 - tW (di-lepton final state): Differential measurements.
 - tW (lepton+jets final state): Inclusive measurements.
 - tZq observation.



CMS t -CHANNEL DIFFERENTIAL CROSS-SECTION MEASUREMENTS

- Measurement performed in the leptonic channel.
- Using data collected by the CMS detector during 2016 (36 fb^{-1}) @ 13 TeV.
- Event selection:
 - Common cuts:
 - Exactly one isolated lepton (e, μ) ($p_{T,e} (p_{T,\mu}) > 35 (26) \text{ GeV}$)
 - Number of jets $\in [2,3]$ ($p_T > 40 \text{ GeV}, |\eta| < 4.7$)
 - Signal region: Exactly 2 jets. Exactly 1 b-tagged (2j1b)
 - Control regions:
 - W+jets CR: 2j0b
 - $t\bar{t}$ CR: 3j2b.
- Two BDTs are used:
 - $\text{BDT}_{t\text{-ch}}$: Discriminates signal from the backgrounds.
 - $\text{BDT}_{t\bar{t}/W}$: Additional sensitivity to the main contributing backgrounds.
- Maximum-likelihood (ML) fit performed to the BDTs and the $m_T(W)$ distributions.
 - Splitted by lepton flavour and lepton charge.

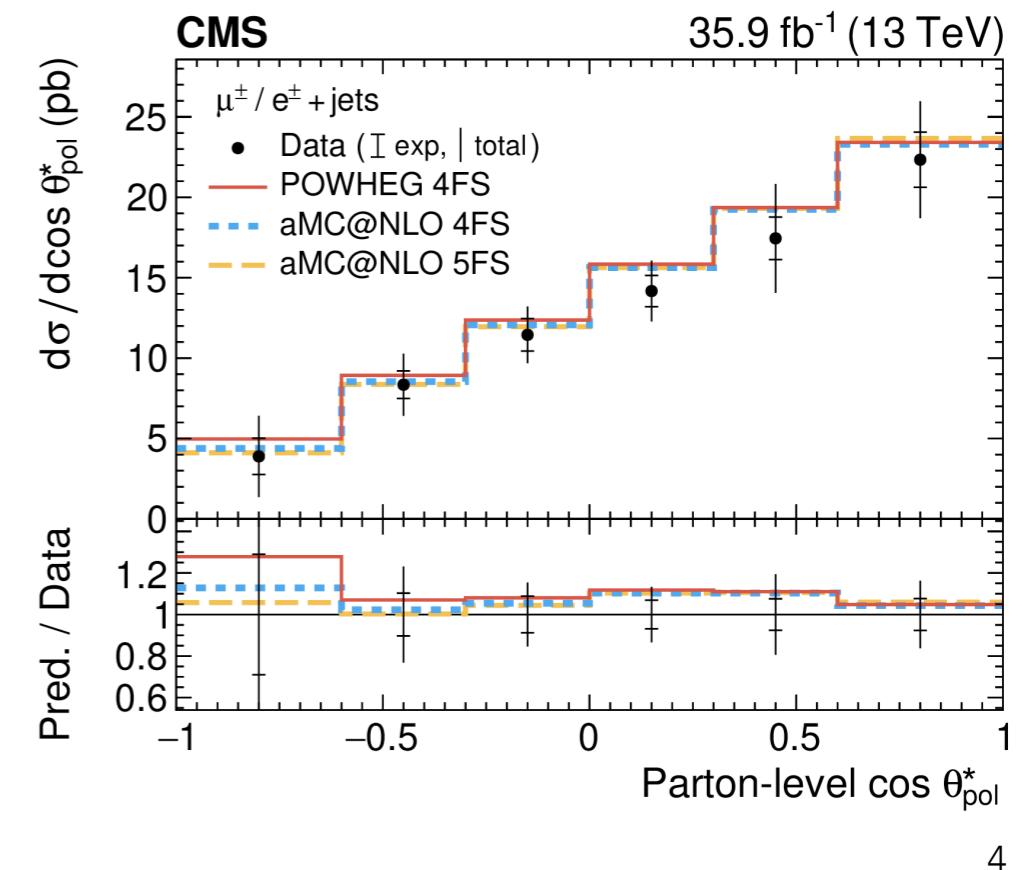
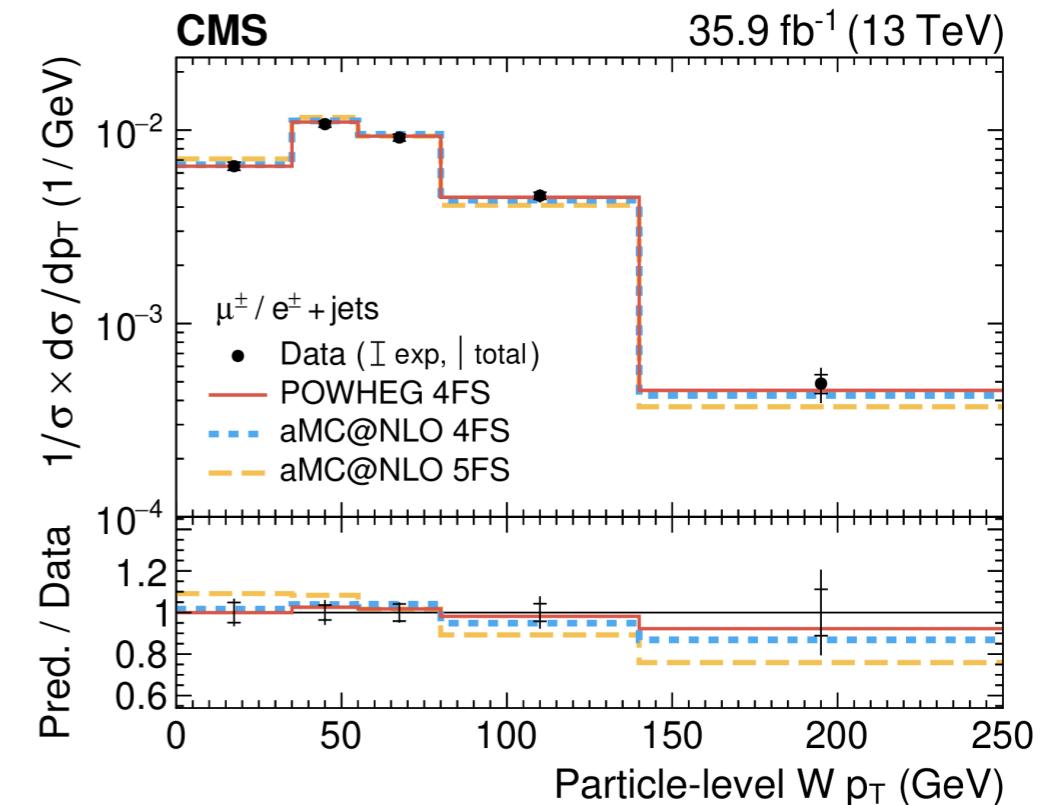
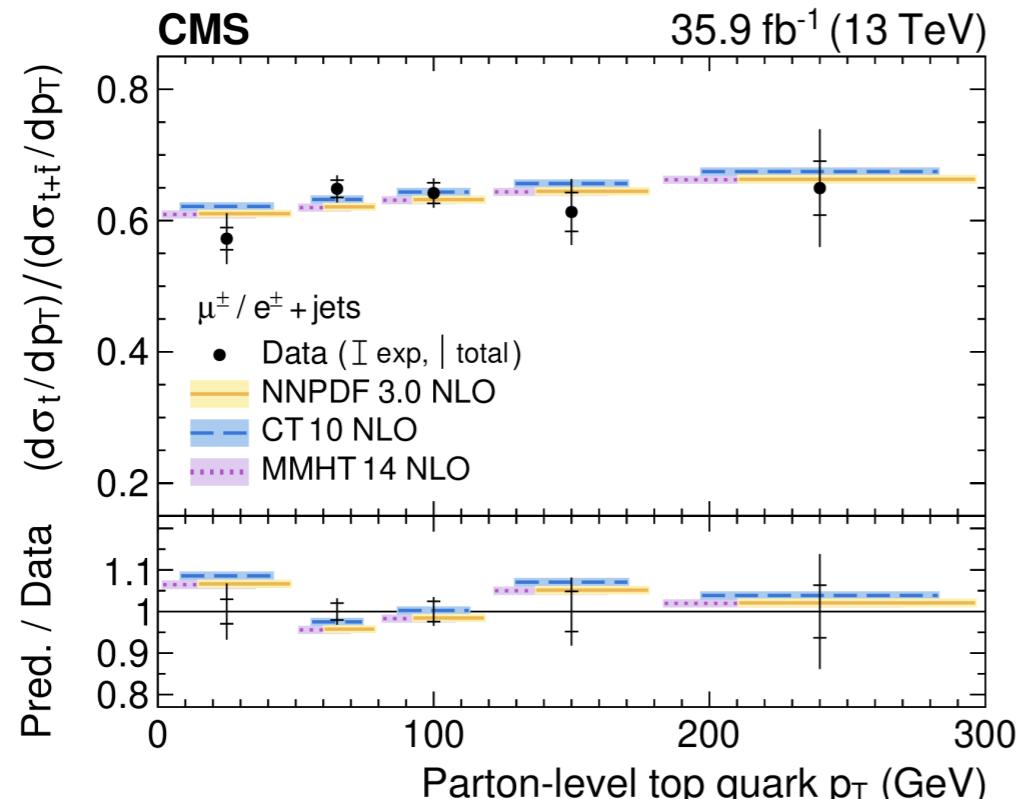
[Eur. Phys. J. C 80 \(2020\) 370](#)



CMS t -CHANNEL DIFFERENTIAL CROSS-SECTION MEASUREMENTS

Eur. Phys. J. C 80 (2020) 370

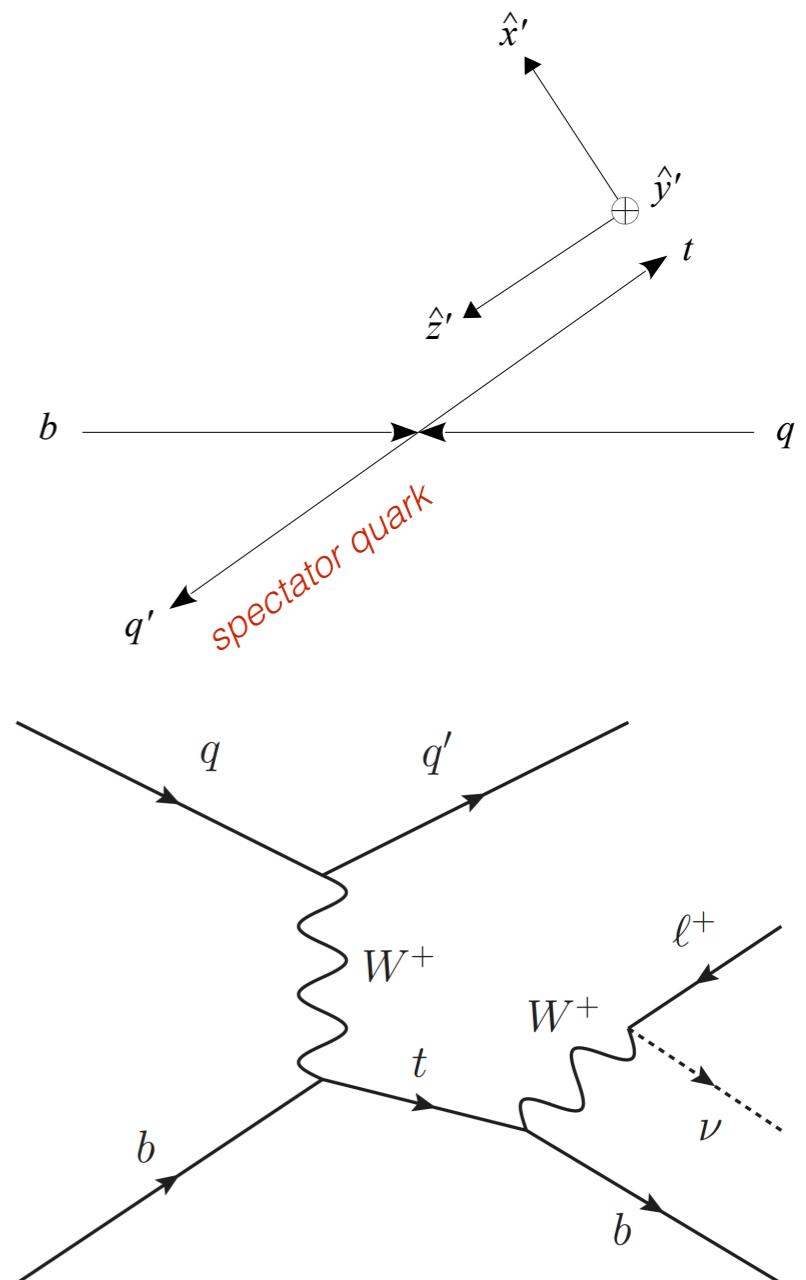
- The signal distributions are unfolded to both the particle and the parton levels and the results are compared with theoretical predictions.
- Differential ratios of the top quark to the sum of the top quark and antiquark.
- Spin asymmetry A_l is determined, sensitive to the top quark polarisation:
 - $A_l = 0.440 \pm 0.070$ ($\sigma_r \approx 16\%$).
 - In agreement with SM predictions (0.436).
- Dominant systematics: Dependence with top-quark mass, $t\bar{t}$ parton shower and colour reconnection.



ATLAS TOP QUARK POLARISATION

- First measurement of all the top-quark polarisation components @ 13 TeV.
- Using data collected by the ATLAS detector during 2015-2018 (139 fb^{-1}).
- In the t-channel at LO single top quarks are produced with their spin aligned along the direction of the down-type quarks.
- The top-quark polarisation can be assessed from the angular distributions of its decay products in the top-quark rest frame.
- Event selection:
 - Common cuts:
 - Exactly one tight charged lepton (e, μ) ($p_T > 30 \text{ GeV}$)
 - Exactly 2 jets. Exactly 1 b-tagged.
 - $E_T^{\text{miss}} > 35 \text{ GeV}$; $m_T(W) > 60 \text{ GeV}$; Additional multijet rejecting cut.
 - Signal region (50% t-channel signal; 25% $t\bar{t}$, 15% W+jets)
 - $t\bar{t}$ & W+jets control regions.

ATLAS-CONF-2021-027 (to appear)

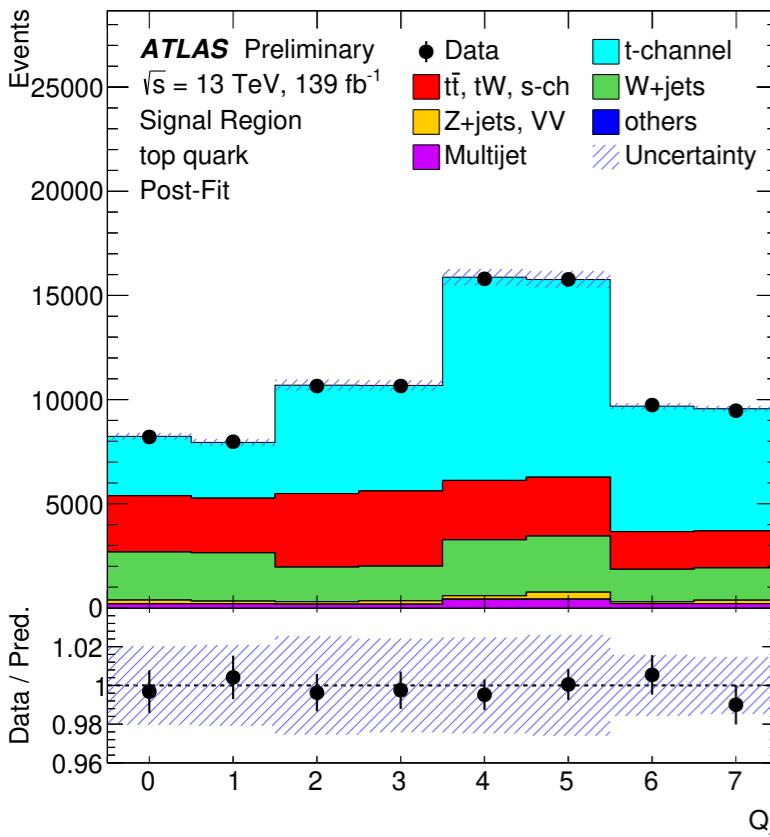
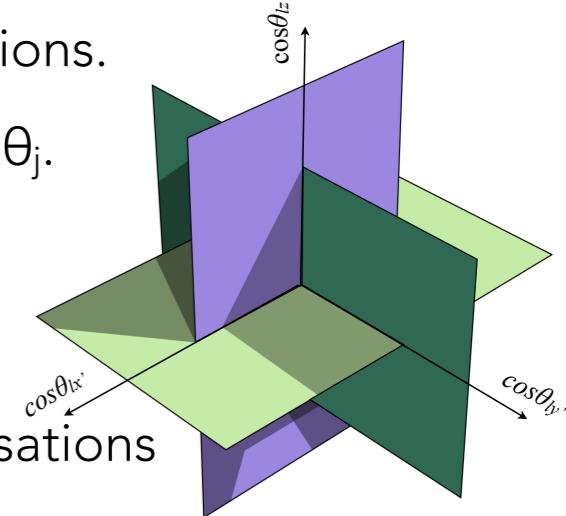
top-quark rest frame

ATLAS TOP QUARK POLARISATION

- Direct measurement of the top quark polarisation components:**

ATLAS-CONF-2021-027 (to appear)

- Profile likelihood fit in 4 regions: 2 signal regions (top & antitop) + 2 control regions.
 - SR: Octant variable Q: Slice the phase space depending on the sign of $\cos \theta_j$.
 - CRs 2-bin splitting based on lepton charge.
- 6 simulated templates with fully polarised states are used in the fit ($P_{x,y,z} = \pm 1$)
- 6 parameters of interest (top and antitop polarisation components) + 3 normalisations ($t\bar{t}$, W+jets & t-channel signal).
- Systematics: Mainly dominated by jet-energy resolution.
- In agreement with SM MC predictions (stat.): $P_x^t = 0.040 \pm 0.012$, $P_z^t = 1.024 \pm 0.015$; $P_x^{\bar{t}} = -0.070 \pm 0.016$, $P_z^{\bar{t}} = -0.967 \pm 0.020$ (P_y is expected to be 0 from CP symmetry).



Parameter	Extracted value	(stat.)
t-channel norm.	+1.045 ± 0.022	(± 0.006)
W+jets norm.	+1.148 ± 0.027	(± 0.005)
tt norm.	+1.005 ± 0.016	(± 0.004)
P_x^t	+0.01 ± 0.18	(± 0.02)
$P_{x'}^t$	-0.02 ± 0.20	(± 0.03)
P_y^t	-0.029 ± 0.027	(± 0.011)
$P_{y'}^t$	-0.007 ± 0.051	(± 0.017)
P_z^t	+0.91 ± 0.10	(± 0.02)
$P_{z'}^t$	-0.79 ± 0.16	(± 0.03)

Uncertainty source	ΔP_x^t	$\Delta P_{x'}^t$	ΔP_y^t	$\Delta P_{y'}^t$	ΔP_z^t	$\Delta P_{z'}^t$
Modelling						
Modelling (t-channel)	±0.037	±0.051	±0.010	±0.015	±0.061	±0.061
Modelling (tt)	±0.016	±0.021	±0.004	±0.016	±0.003	±0.016
Modelling (other)	±0.013	±0.031	±0.003	±0.006	±0.026	±0.043
Experimental						
Jet energy scale	+0.045	+0.048	+0.005	+0.007	±0.033	±0.025
Jet energy resolution	±0.166	±0.185	±0.021	±0.040	±0.070	±0.130
Jet flavour tagging	±0.004	±0.002	<0.001	±0.001	±0.007	±0.009
Other experimental uncertainties	±0.015	±0.029	±0.002	±0.007	±0.014	±0.026
Multijet estimation	±0.008	±0.021	<0.001	±0.001	±0.008	±0.013
Luminosity	±0.001	±0.001	<0.001	<0.001	<0.001	<0.001
Simulation statistics	±0.020	±0.024	±0.008	±0.015	±0.017	±0.031
Total systematic uncertainty	±0.174	±0.199	±0.025	±0.048	±0.096	±0.153
Total statistical uncertainty	±0.017	±0.025	±0.011	±0.017	±0.022	±0.034

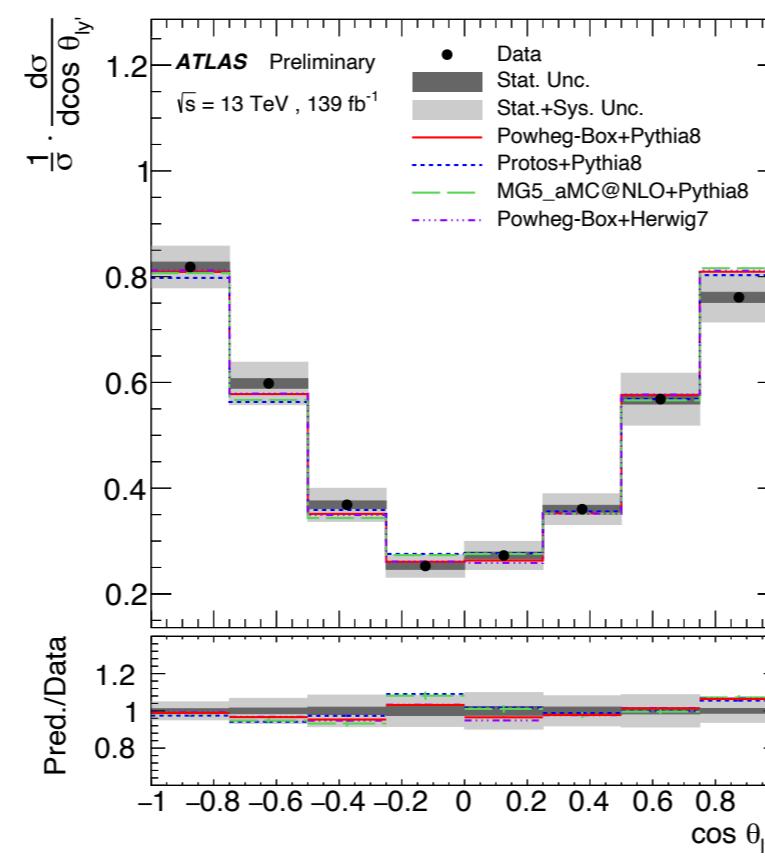
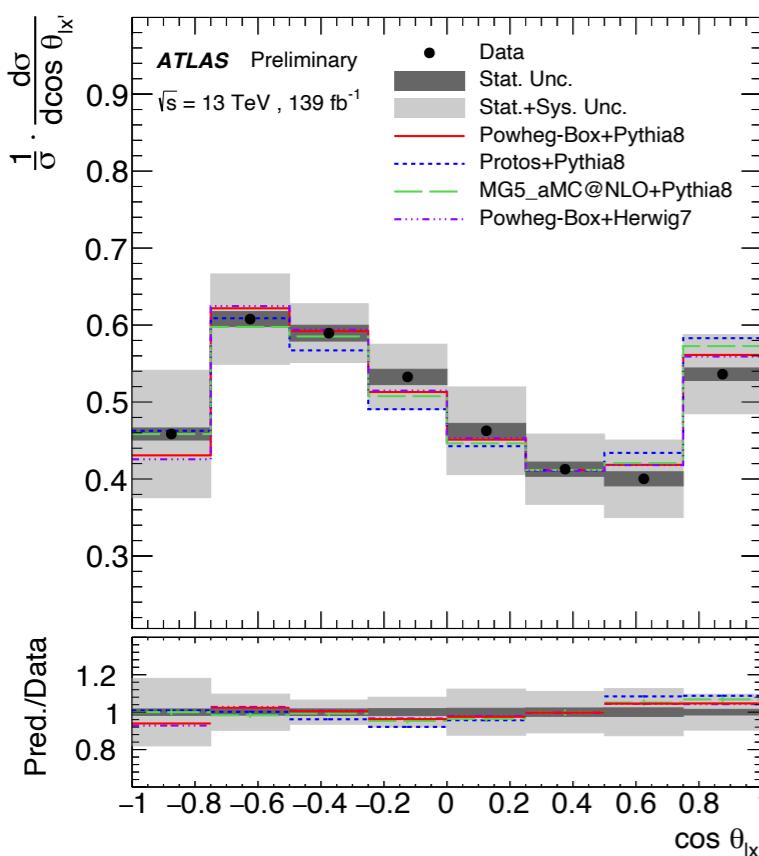
First measurement ever!

ATLAS TOP QUARK POLARISATION

- Normalised differential cross-section measurements:

ATLAS-CONF-2021-027 (to appear)

- As a function of the three angular distributions sensitive to new physics effects in the tWb vertex.
- The normalisations of the W+jets and top-quark backgrounds and the t -channel signal are constrained with a maximum likelihood fit to the data in the signal and control regions.
- After background subtraction the distributions are unfolded to the particle-level in a fiducial region
- Systematics: Mainly dominated by jet-energy resolution, jet-energy scale and t -channel modelling.



	C_{tW}		C_{itW}	
	68% CL	95% CL	68% CL	95% CL
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]

Best limits so far from high-energy experiments!

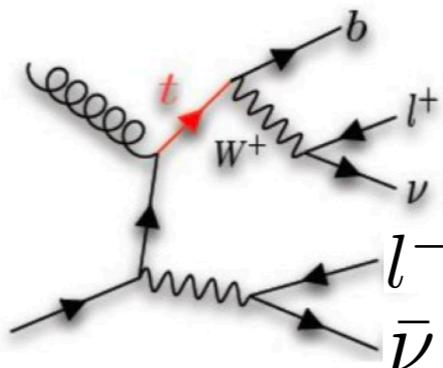
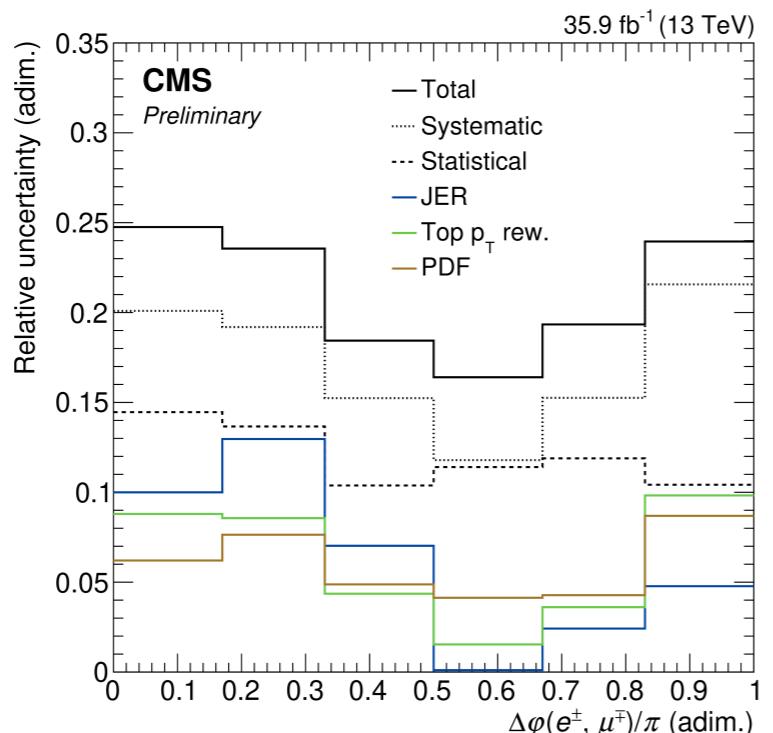
See also Laura Barranco's talk

$$\sigma(C_{tW}, C_{itW}) \propto \left| O_{\text{SM}} + \frac{C_{tW}}{\Lambda^2} \cdot O_{tW} + \frac{C_{itW}}{\Lambda^2} \cdot O_{itW} \right|_{\text{production}}^2 \cdot \left| O_{\text{SM}} + \frac{C_{tW}}{\Lambda^2} \cdot O_{tW} + \frac{C_{itW}}{\Lambda^2} \cdot O_{itW} \right|_{\text{decay}}^2$$

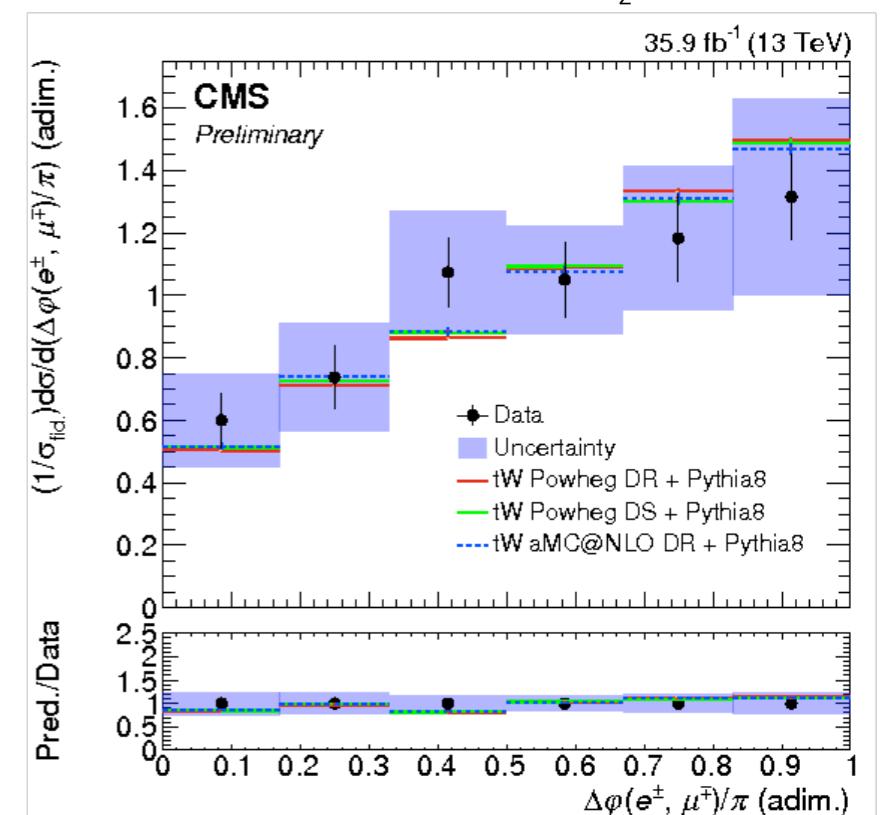
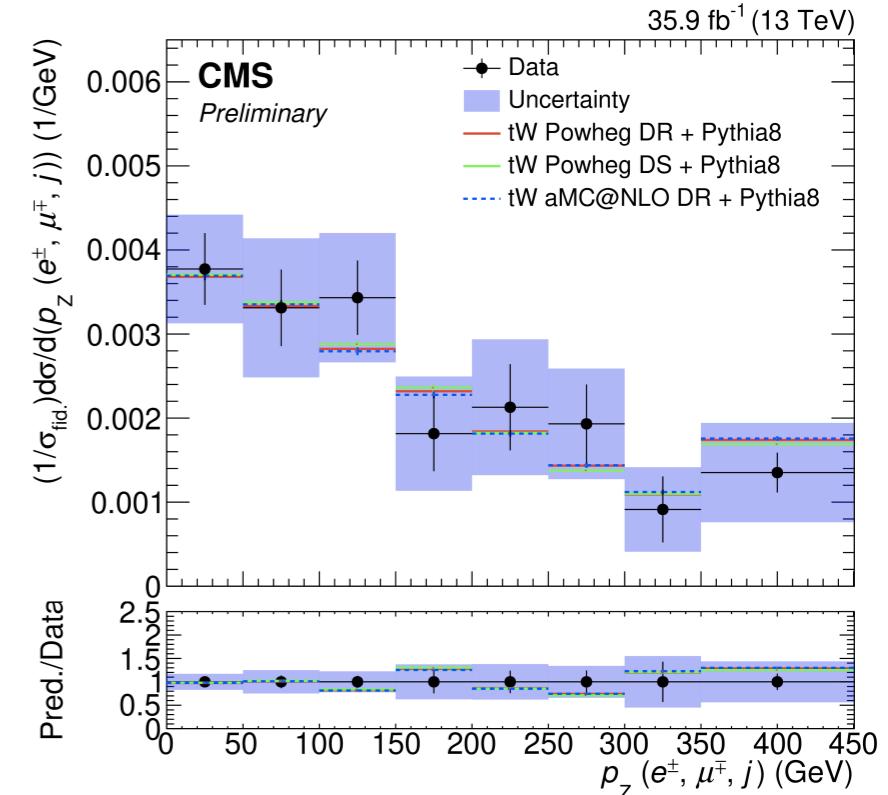
- The results are interpreted in an EFT context to set limits on Wilson coefficients.
- A profile likelihood fit is performed including morphing templates to simulate BSM effects.

CMS tW DIFFERENTIAL CROSS-SECTION MEASUREMENTS

- Measurement performed in the dilepton channel.
- Using data collected by the CMS detector during 2016 (36 fb^{-1}) @ 13 TeV.
- Event selection (cut-and-count):
 - 1 opposite-sign different-flavour lepton pair.
 - $p_T(l_1) > 25 \text{ GeV}, p_T(l_2) > 20 \text{ GeV}$
 - $m_{e\mu} > 20 \text{ GeV}$
 - Exactly 1 jet. Exactly 1 b-tagged. No loose jets.
($p_T \in [20, 30] \text{ GeV}$)
- The results are unfolded to the particle level and the measurements are performed in a fiducial region.
- Results in agreement with SM predictions.
- Systematics: Mainly dominated by JER and JES.



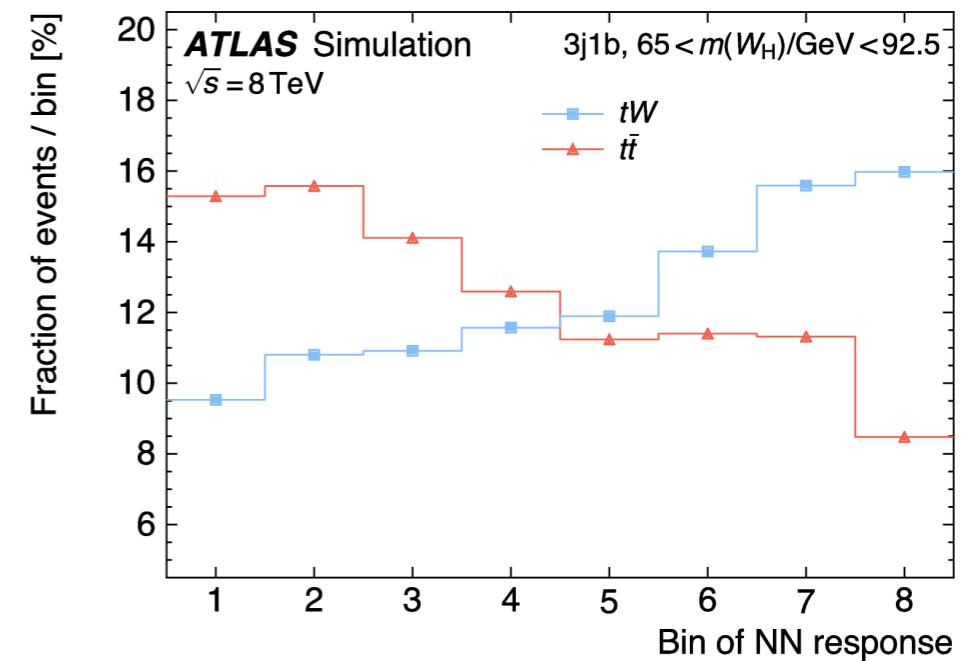
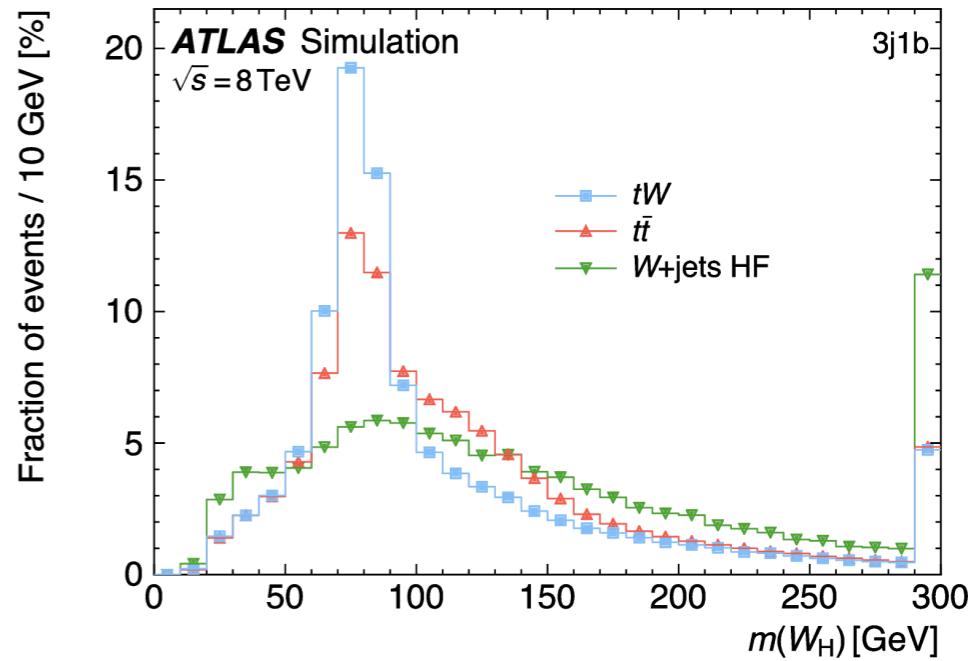
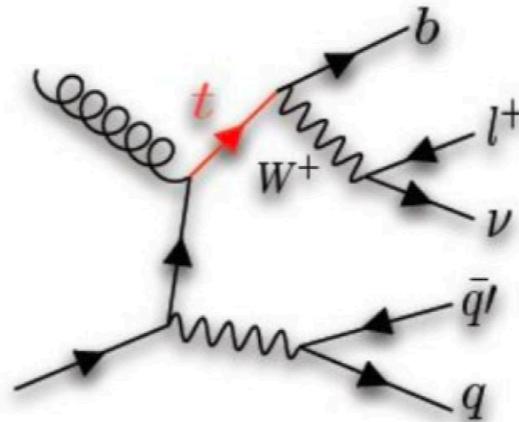
CMS-PAS-TOP-19-003



ATLAS tW CROSS-SECTION MEASUREMENT

[arXiv:2007.01554](https://arxiv.org/abs/2007.01554)

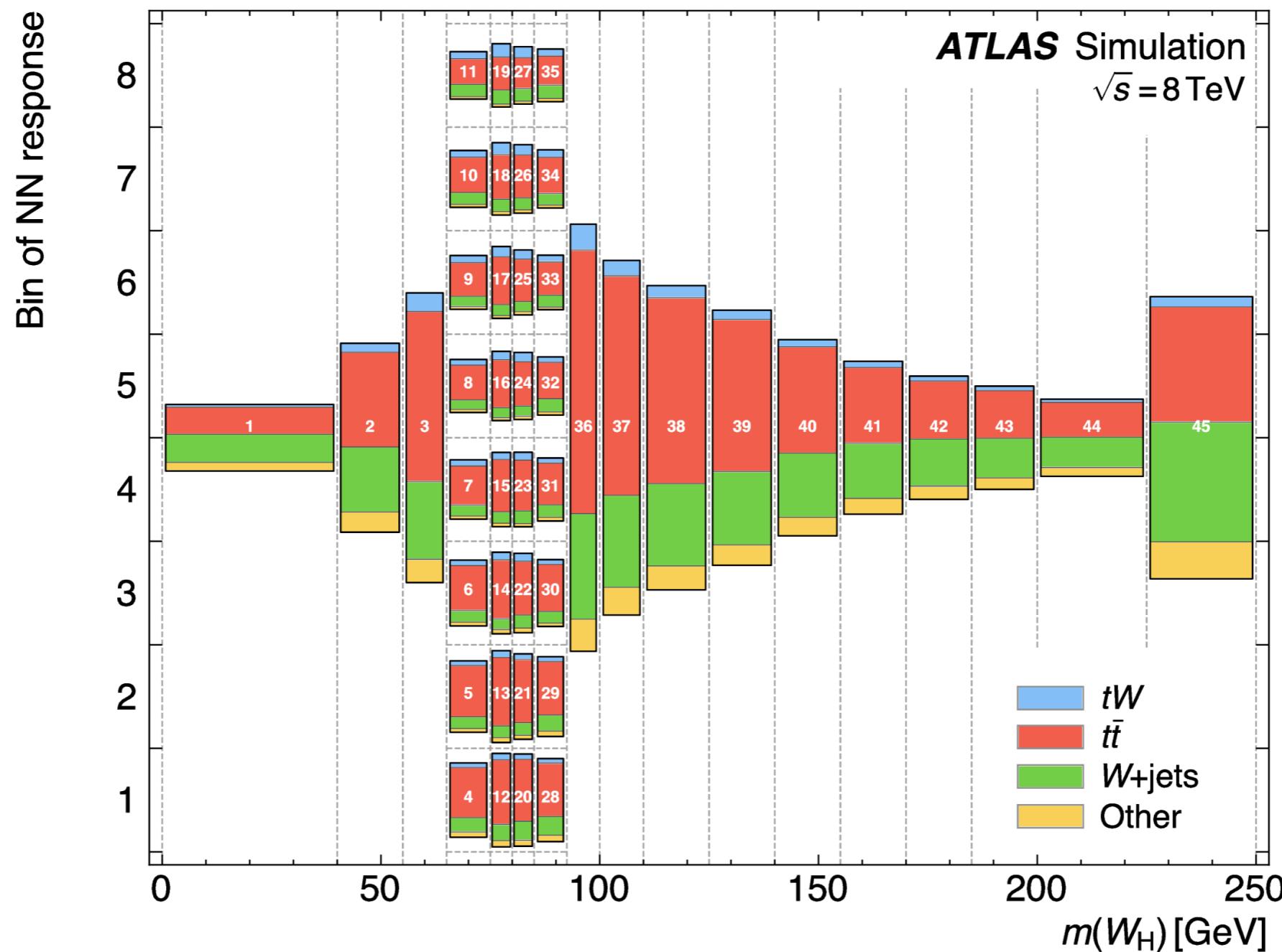
- Measurement performed in the **lepton+jets** channel.
- Using data collected by the ATLAS detector during 2012 (20.2 fb^{-1}) **@ 8 TeV**.
- Event selection:
 - Common cuts:
 - Exactly one isolated lepton (e, μ) ($p_T > 30 \text{ GeV}$)
 - $E_T^{\text{miss}} > 30 \text{ GeV}$
 - $m_T(W_L) > 50 \text{ GeV}$
 - At least 3 jets ($p_T > 30 \text{ GeV}, |\eta| < 2.4$)
 - Signal region: Exactly 3 jets. Exactly one b-tagged.
 - Composition: 5% tW , 58% $t\bar{t}$ (main background)
 - $t\bar{t}$ validation region: Exactly 4 jets. Exactly 2 b-tagged.
 - **Neural network** (NN) is used to further discriminate between the tW signal and the $t\bar{t}$ background:
 - Trained on $65 \text{ GeV} < m(W_H) < 92.5 \text{ GeV}$.



ATLAS tW CROSS-SECTION MEASUREMENT

arXiv:2007.01554

- A 2D discriminant is built from the output of the NN (trained on $65 \text{ GeV} < m(W_H) < 92.5 \text{ GeV.}$) and the $m(W_H)$ distribution.



ATLAS tW CROSS-SECTION MEASUREMENT

[arXiv:2007.01554](https://arxiv.org/abs/2007.01554)

- Profile likelihood fit is performed **in the SR**.
- The **2D discriminant** is rearranged on a one-dimensional distribution to perform the fit.
- Systematics: Mainly dominated by signal and $t\bar{t}$ radiation, jet-energy-scale and limited size of the MC samples.

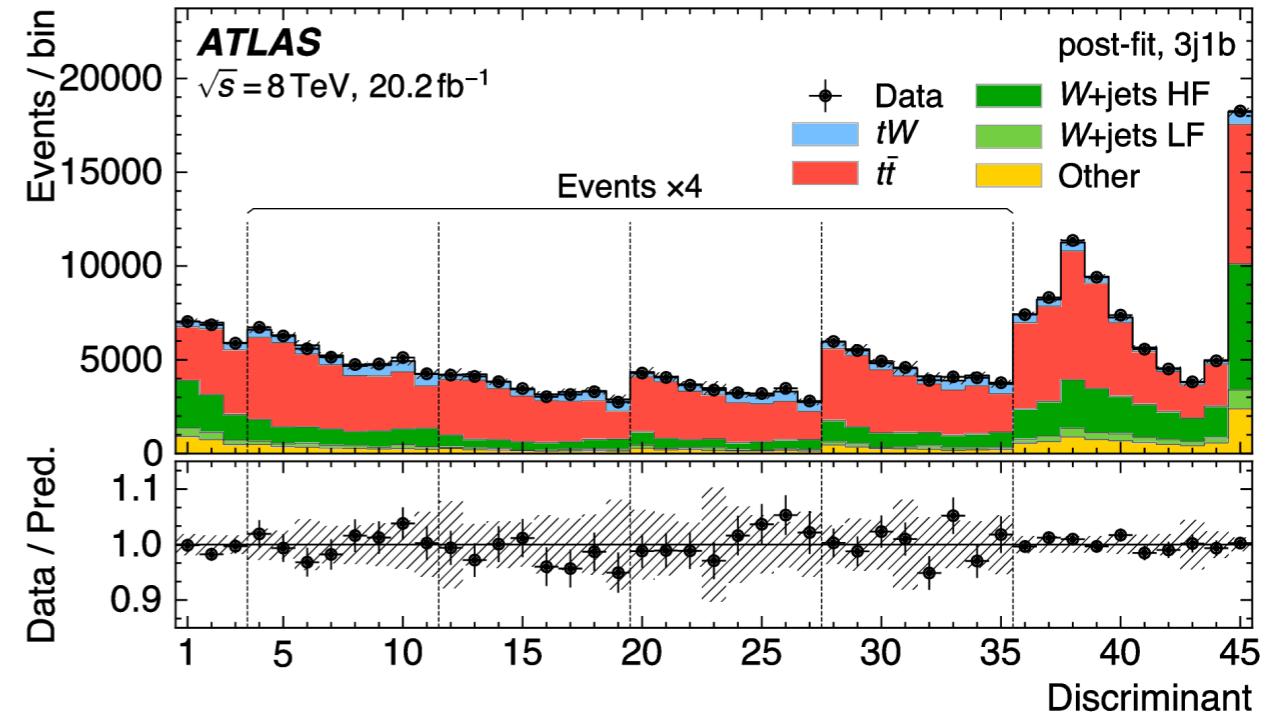
$$\sigma_{tW}^{\text{meas.}} = 26 \pm 7 \text{ pb}$$

$(\sigma_r \approx 27\%)$

- Evidence! Observed (expected significance): **4.5σ (3.9σ)**.
- In agreement with the SM predictions:

$$\sigma_{tW}^{\text{th.}} = 22.4 \pm 1.5 \text{ pb} \quad (\sigma_r \approx 7\%)$$

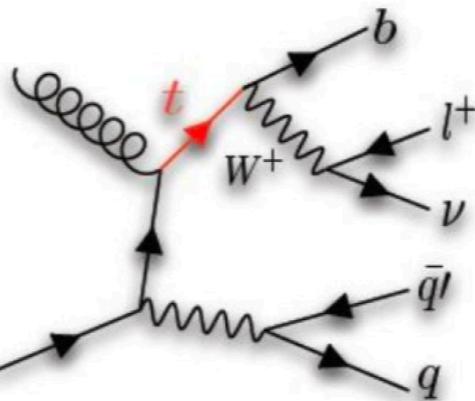
(NLO+NNLL)



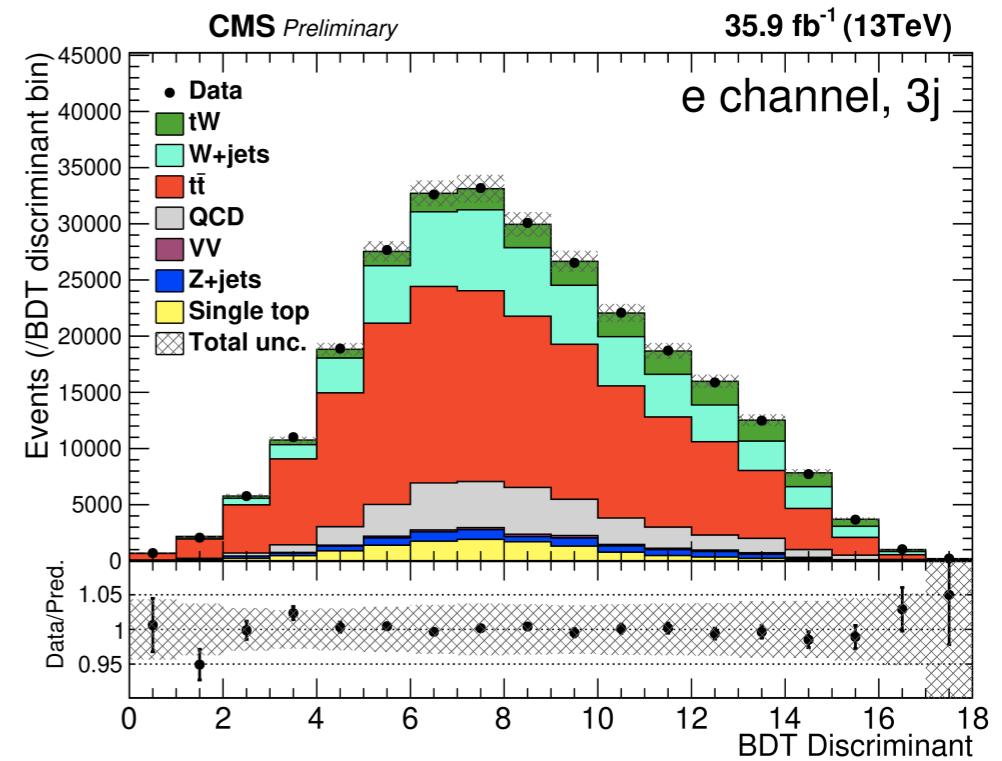
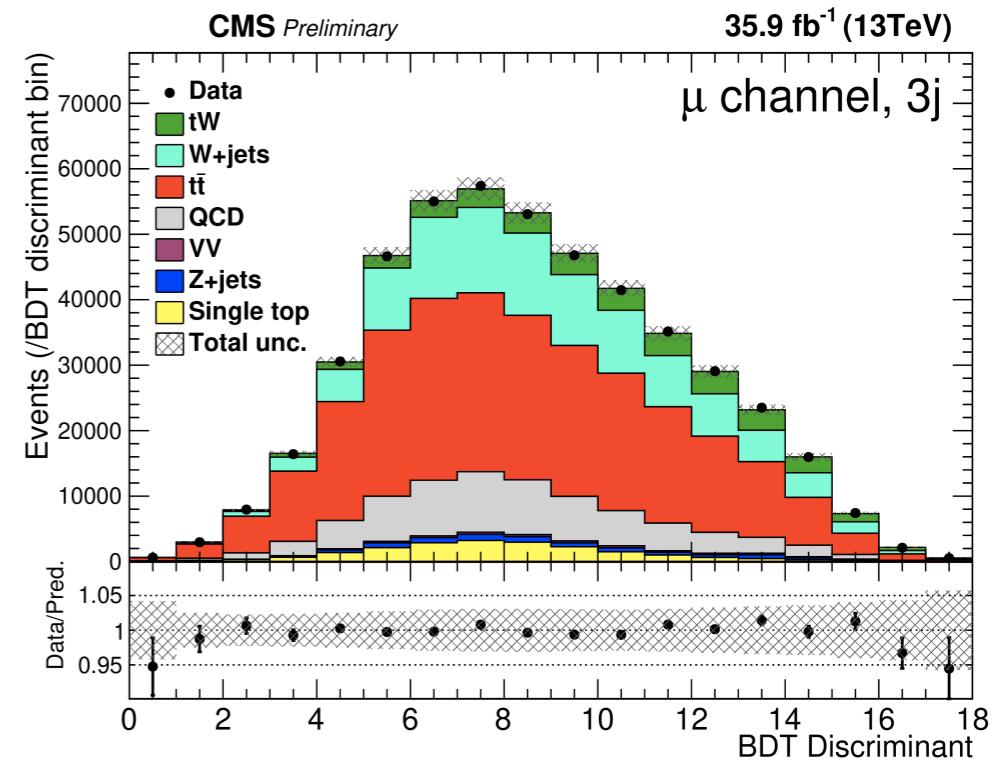
Source	Uncertainty [%]
Jet energy scale	10
b -tagging	8
Jet energy resolution	7
E_T^{miss} reconstruction	7
Lepton reconstruction	4
Luminosity	3
Jet vertex fraction	3
<hr/>	
$t\bar{t}$ radiation	10
tW radiation	9
$tW-t\bar{t}$ interference	7
$t\bar{t}$ cross-section normalisation	6
Other background cross-section normalisations	5
tW and $t\bar{t}$ parton shower	4
tW and $t\bar{t}$ NLO matching	3
PDF	1
<hr/>	
Model statistics	11
Data statistics	4
Total	27

CMS tW CROSS-SECTION MEASUREMENT

- Measurement performed in the **lepton+jets** channel.
- Using data collected by the CMS detector during 2016 (36 fb^{-1}) **@ 13 TeV**.
- Event selection:
 - Common cuts:
 - Exactly one isolated lepton (e, μ) ($p_{T,e} (p_{T,\mu}) > 30 (26) \text{ GeV}$)
 - Number of jets $\in [2,4]$ ($p_T > 30 \text{ GeV}, |\eta| < 2.4$)
 - Exactly one b-tagged jet.
 - Signal region: Exactly 3 jets.
 - Composition: 6% tW , 58% $t\bar{t}$ (main background)
 - $t\bar{t}$ control region: Exactly 4 jets.
 - $W+\text{jets}$ & QCD control region: Exactly 2 jets.
 - The signal and control regions are splitted by lepton flavour.
 - A **BDT** is used to further enhance the discrimination between the tW signal and the $t\bar{t}$.



[CMS-PAS-TOP-20-002](#)



CMS tW CROSS-SECTION MEASUREMENT

- A profile likelihood fit on the shape of the **BDT discriminants** is performed **in the signal and control regions**.
- Systematics: Mainly dominated by QCD & $W+jets$ normalisation, and jet-energy-scale.
- Measured signal strength:

$$\mu = 1.24 \pm 0.18$$

- Observation! $>5\sigma$
- Measured inclusive cross-section:

$$\sigma_{tW} = 89 \pm 4 \text{ (stat.)} \pm 12 \text{ (syst.) pb}$$

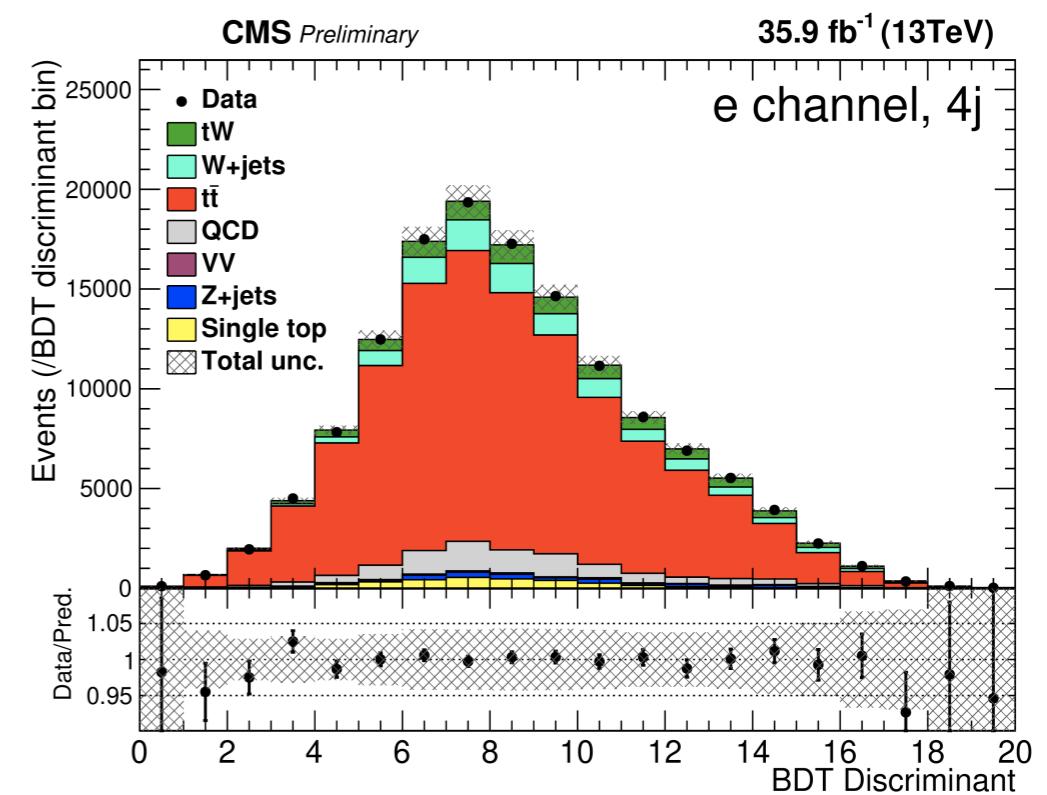
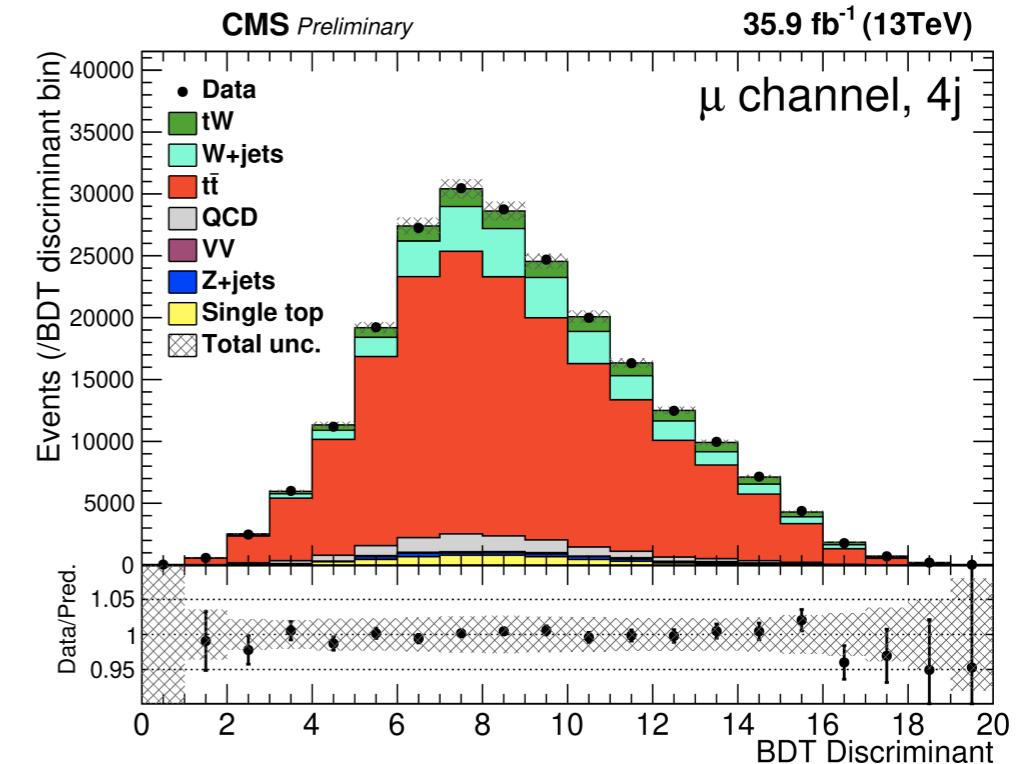
$(\sigma_r \approx 13\%)$

- In agreement with SM predictions (within 2σ):

$$\sigma_{tW}^{th.} = 71.7 \pm 3.8 \text{ pb} \quad (\sigma_r \approx 5\%)$$

(NLO+NNLL)

CMS-PAS-TOP-20-002



CMS tW CROSS-SECTION MEASUREMENT

- A profile likelihood fit on the shape of the **BDT discriminants** is performed **in the signal and control regions**.
- Systematics: Mainly dominated by QCD & W+jets normalisation, and jet-energy-scale.
- Measured signal strength:

$$\mu = 1.24 \pm 0.18$$

- Observation! $>5\sigma$
- Measured inclusive cross-section:

$$\sigma_{tW} = 89 \pm 4 \text{ (stat.)} \pm 12 \text{ (syst.) pb}$$

$(\sigma_r \approx 13\%)$

- In agreement with SM predictions (within 2σ):

$$\sigma_{tW}^{th.} = 71.7 \pm 3.8 \text{ pb} \quad (\sigma_r \approx 5\%)$$

(NLO+NNLL)

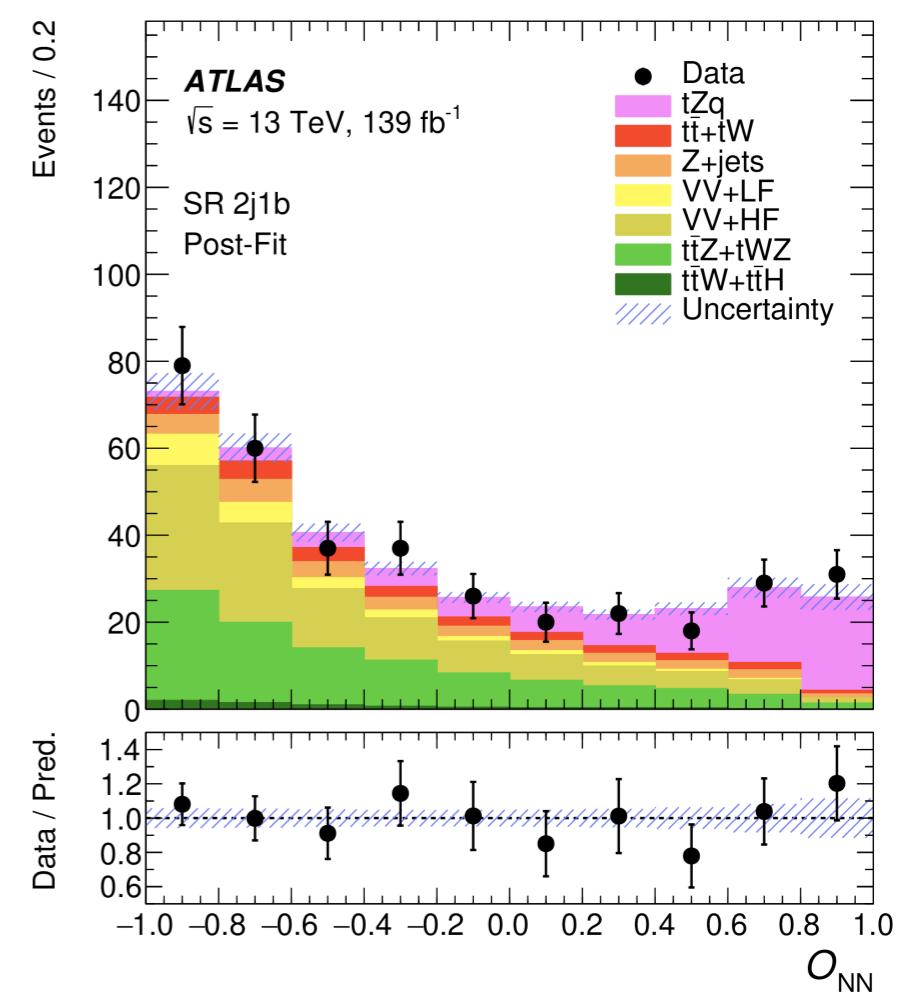
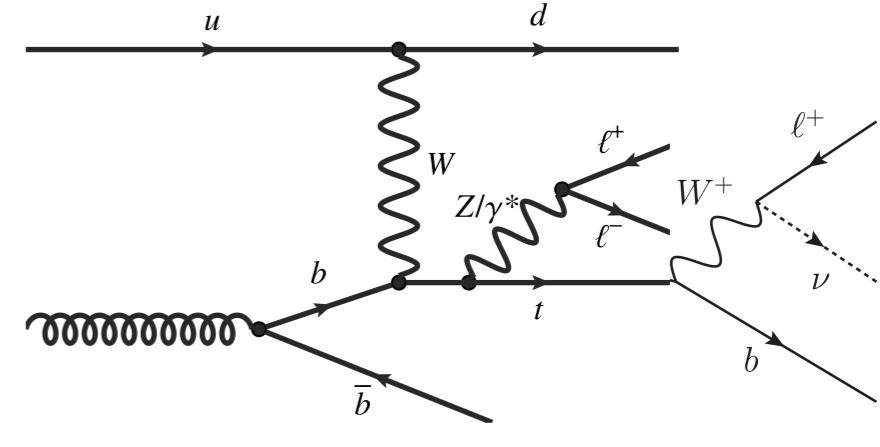
CMS-PAS-TOP-20-002

Source	Relative uncertainty (%)
QCD normalization	7
W+jets normalization	6
Z+jets normalization	3
Single top normalization	1
t̄t normalization	1
VV normalization	< 1
JES	6
b-tagging	4
Luminosity	3
LES	2
Trigger	1
JER	1
Mistag	< 1
Unclustered MET	< 1
Pileup	< 1
h_{damp}	4
DR/DS	3
MC tune	3
Colour reconnection	1
PDF	1
ME/PS matching	1
Final state radiation	< 1
Initial state radiation	< 1
Total systematic uncertainty	14
Statistical uncertainty	5
Total uncertainty	15

ATLAS tZq OBSERVATION

JHEP 07 (2020) 124

- Using data collected by the ATLAS detector during 2015-2018 (139 fb^{-1}) @ 13 TeV.
- Event selection:
 - A total of 8 regions are used in this analysis:
 - 2 SRs & 6 CRs for the main backgrounds: $t\bar{t}Z$, $t\bar{t}$ & Diboson
 - Exactly 3 leptons (e, μ) are required in the final state. The regions differ in the number of jets and b-tagged jets.
 - Signal regions: 2j1b, 3j1b.
 - One opposite-sign, same-flavour (OSSF) lepton pair is required to reconstruct the Z boson.
 - In the $t\bar{t}$ CR, one opposite-sign, different-flavour (OSDF) is required instead.
 - NN used to further distinguish the signal from the backgrounds.



ATLAS tZq OBSERVATION

[JHEP 07 \(2020\) 124](#)

- Profile likelihood fit performed in the signal and control regions.
- The NN output is used in the SRs and the $t\bar{t}Z$ CRs.
- The reconstructed transverse mass of the W boson is used in the diboson CRs.
 - Discriminates between the Z+jets and the diboson backgrounds.
- Total events yields used in the $t\bar{t}$ CRs.
- The results are mainly dominated by statistical uncertainties.

$$\sigma_{tl^+l^-q} = 97 \pm 13 \text{ (stat.)} \pm 7 \text{ (syst.) fb}$$

$(\sigma_r \approx 13\%)$

- Observation! $>5\sigma$
- In agreement with SM predictions:

$$\sigma_{tZq}^{th.} = 102^{+5}_{-2} \text{ fb} \quad (\sigma_r \approx 5\%)$$

- Compatible with previous results from CMS:
[\(Phys. Rev. Lett. 122, 132003 \(2019\)\)](#)

$$\sigma_{tl^+l^-q} = 111 \pm 13 \text{ (stat.)} {}^{+11}_{-9} \text{ (syst.) fb}$$

$(\sigma_r \approx 12\%)$

Uncertainty source	$\Delta\sigma/\sigma [\%]$
Prompt-lepton background modelling and normalisation	3.3
Jets and E_T^{miss} reconstruction and calibration	2.0
Lepton reconstruction and calibration	2.0
Luminosity	1.7
Non-prompt-lepton background modelling	1.6
Pile-up modelling	1.2
MC statistics	1.0
tZq modelling (QCD radiation)	0.8
tZq modelling (PDF)	0.7
Jet flavour tagging	0.4
Total systematic uncertainty	7.0
Data statistics	12.6
$t\bar{t} + tW$ and Z+jets normalisation	2.1
Total statistical uncertainty	12.9

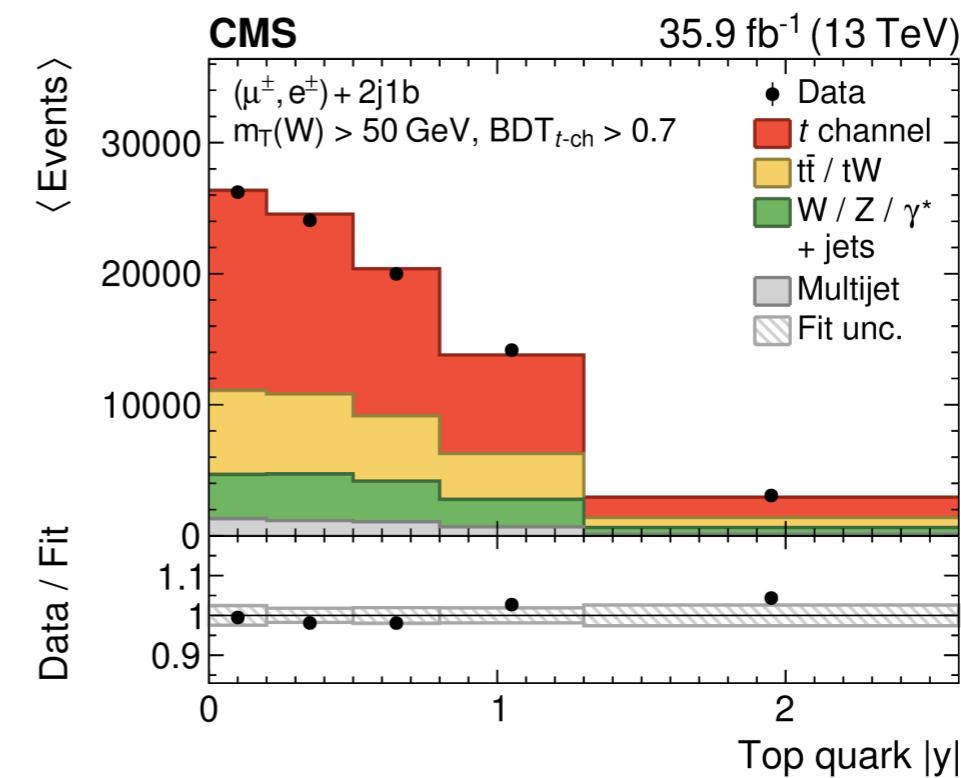
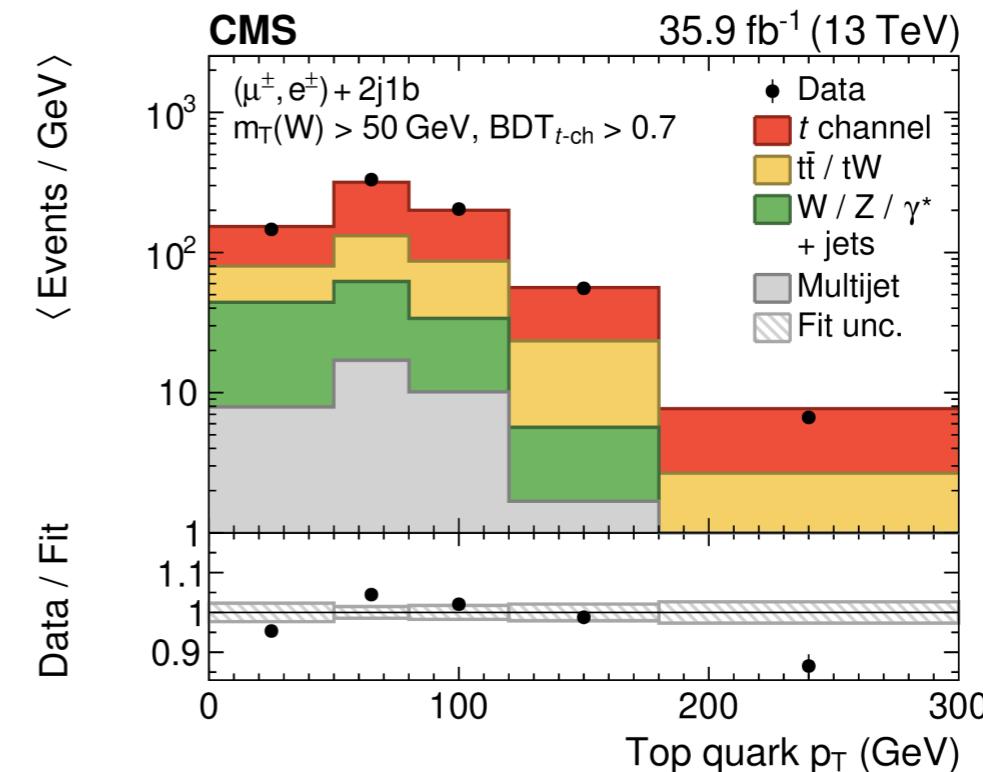
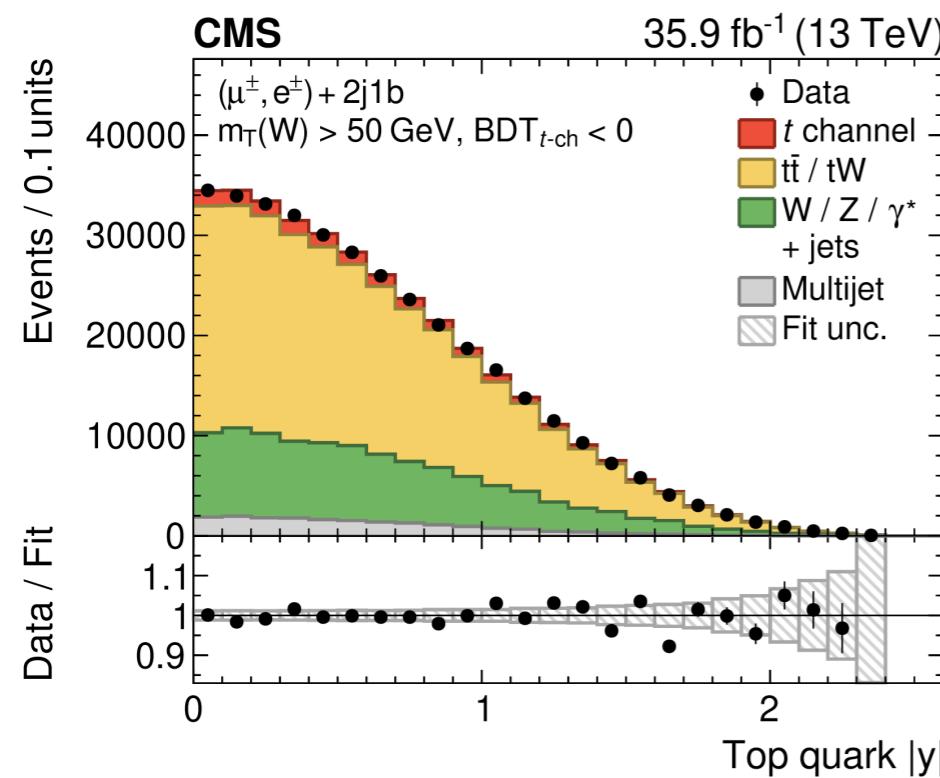
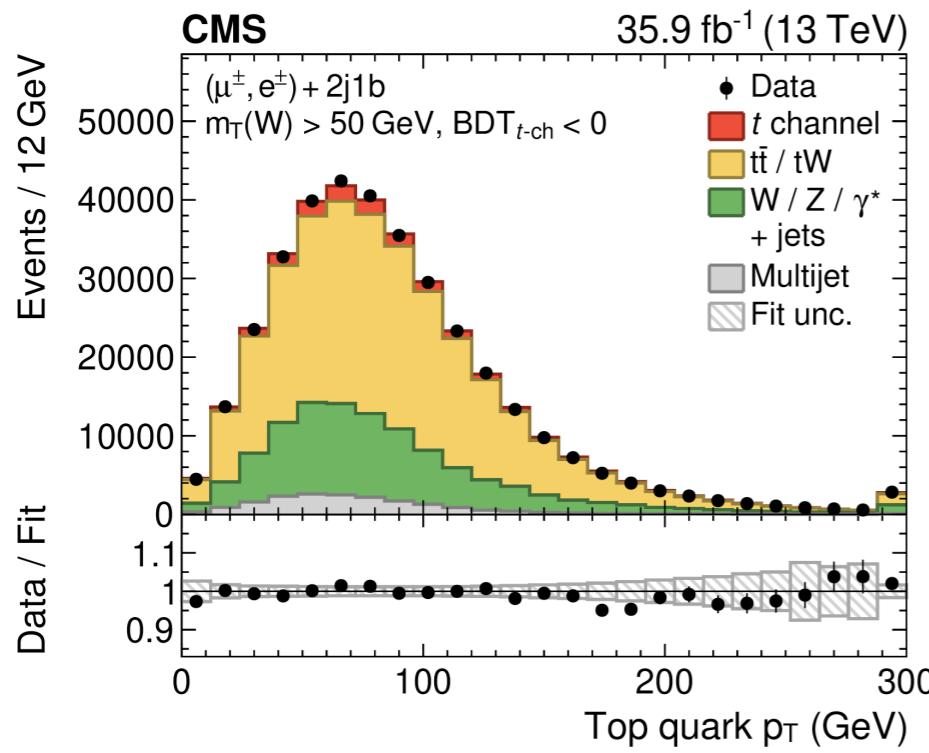
SUMMARY

- Single-top-quark cross-section measurements:
 - t-channel and tW (di-lepton channel) differential cross-section measurements.
 - First measurements on the tW lepton+jets final state.
 - Analyses exploit multivariate techniques to achieve a relatively clean signal.
 - No deviations from the SM are seen.
- Rare top processes:
 - First observation of tZq by ATLAS.
 - Results are compatible with previous observations by CMS.
- Top quark polarisation:
 - First measurement of the full polarisation vectors for both top quarks and antiquarks.
 - Normalised differential cross-section measurements sensitive to new physics in the tWb vertex.
 - The results are interpreted in an EFT context: $C_{tw} \in [-0.7, 1.5]$, $C_{itw} \in [-0.7, 0.2]$. Best limits so far from high-energy experiments in the imaginary part of the O_{tw} dipole operator.

BACKUP

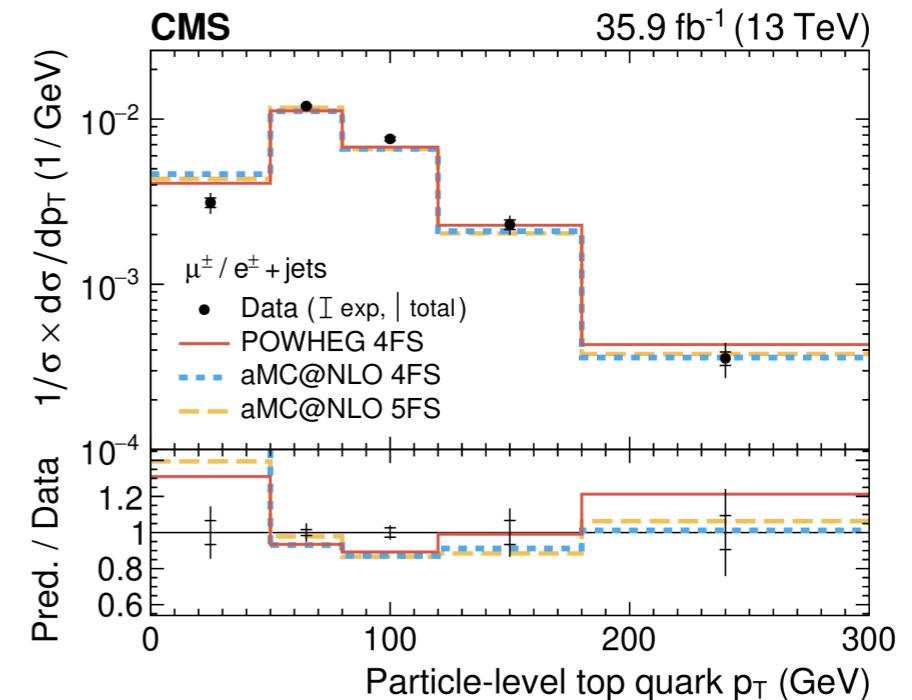
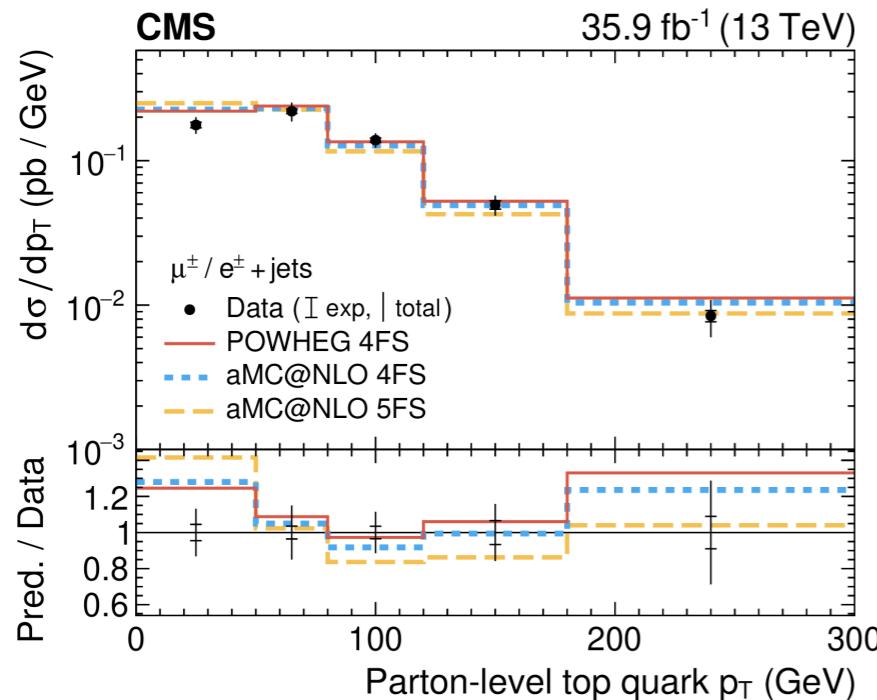
CMS t -CHANNEL DIFFERENTIAL CROSS-SECTION MEASUREMENTS

- The modelling of the backgrounds has been validated in signal- and background-enriched regions:



CMS t -CHANNEL DIFFERENTIAL CROSS-SECTION MEASUREMENTS

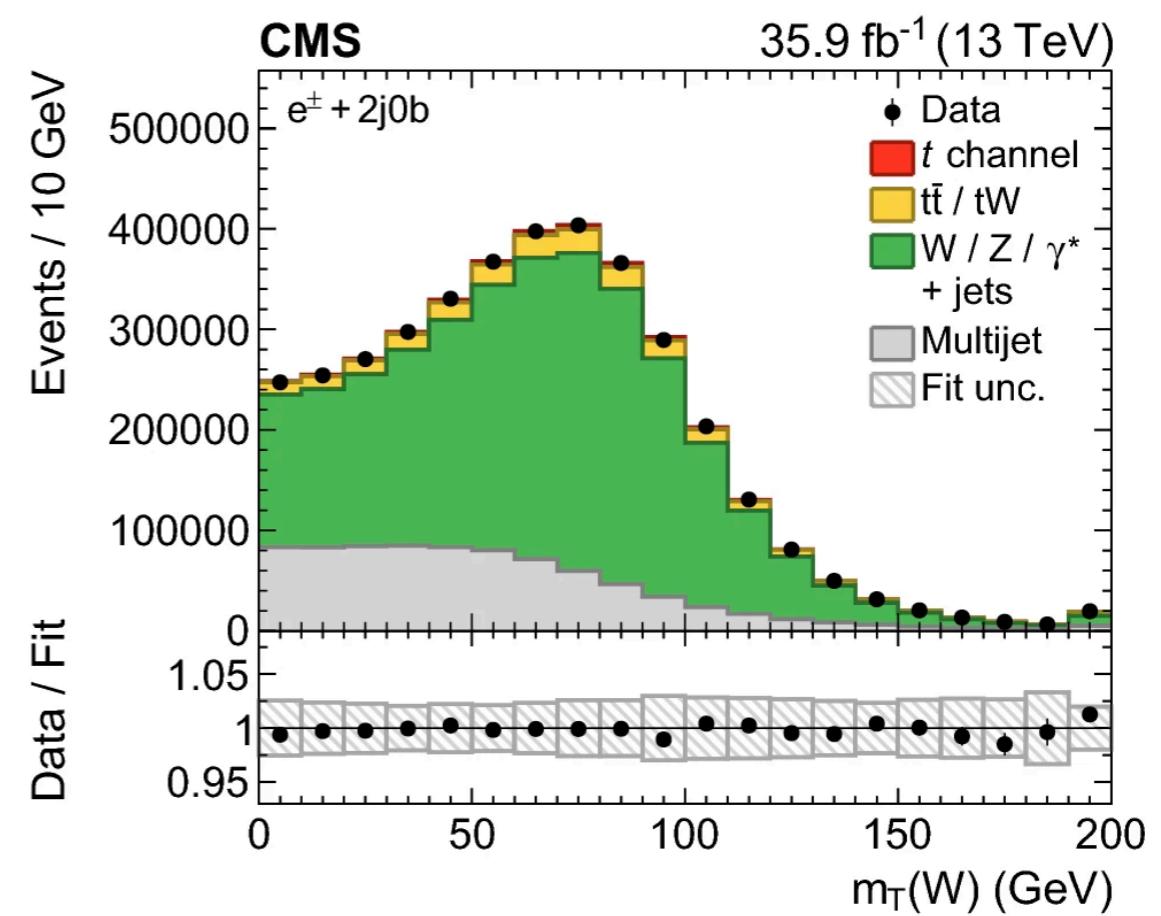
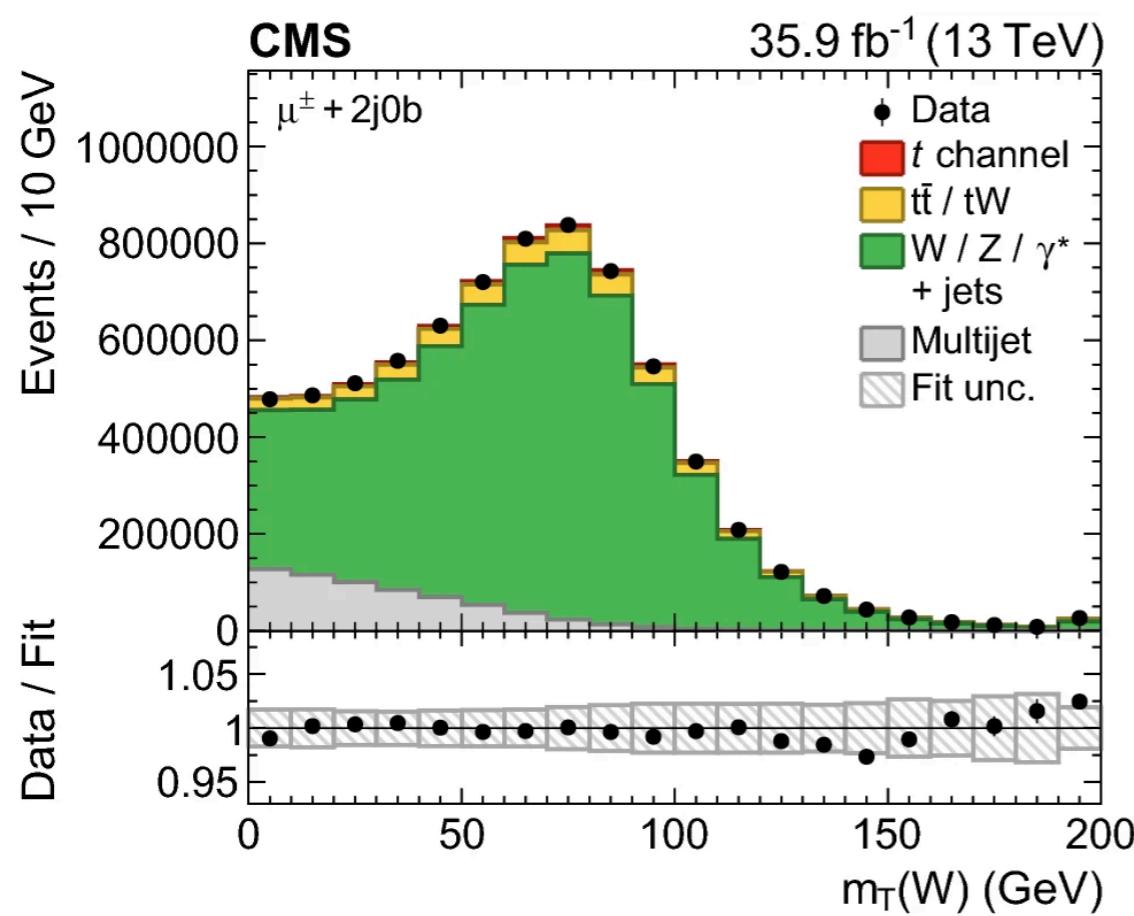
- In general nice agreement between the data and the expectations.
- However, some tensions are seen in the differential distributions as a function of the top quark p_T .



Observable	χ^2/dof values at the parton (particle) level					
	POWHEG		MADGRAPH5_AMC@NLO			
	4FS	4FS	5FS	5FS		
Top quark p_T	Abs	2.6 (2.6)	3.6 (4.4)	7.4 (3.3)		
	Norm	2.5 (2.4)	3.6 (3.6)	7.4 (3.3)		
Charged lepton p_T	Abs	0.7 (0.6)	0.6 (0.5)	1.5 (0.9)		
	Norm	0.7 (0.6)	0.6 (0.5)	1.6 (1.1)		
W boson p_T	Abs	0.2 (0.3)	0.3 (0.4)	1.6 (1.1)		
	Norm	<0.1 (<0.1)	0.2 (0.5)	1.4 (1.4)		
Top quark rapidity	Abs	0.6 (0.6)	0.5 (0.4)	0.4 (0.4)		
	Norm	0.6 (0.6)	0.6 (0.4)	0.5 (0.3)		
Charged lepton rapidity	Abs	1.3 (1.5)	1.4 (1.5)	1.5 (1.8)		
	Norm	1.5 (1.7)	1.5 (1.8)	1.7 (2.3)		
Polarisation angle	Abs	0.2 (0.3)	0.1 (<0.1)	0.1 (<0.1)		
	Norm	<0.1 (0.1)	<0.1 (<0.1)	<0.1 (<0.1)		

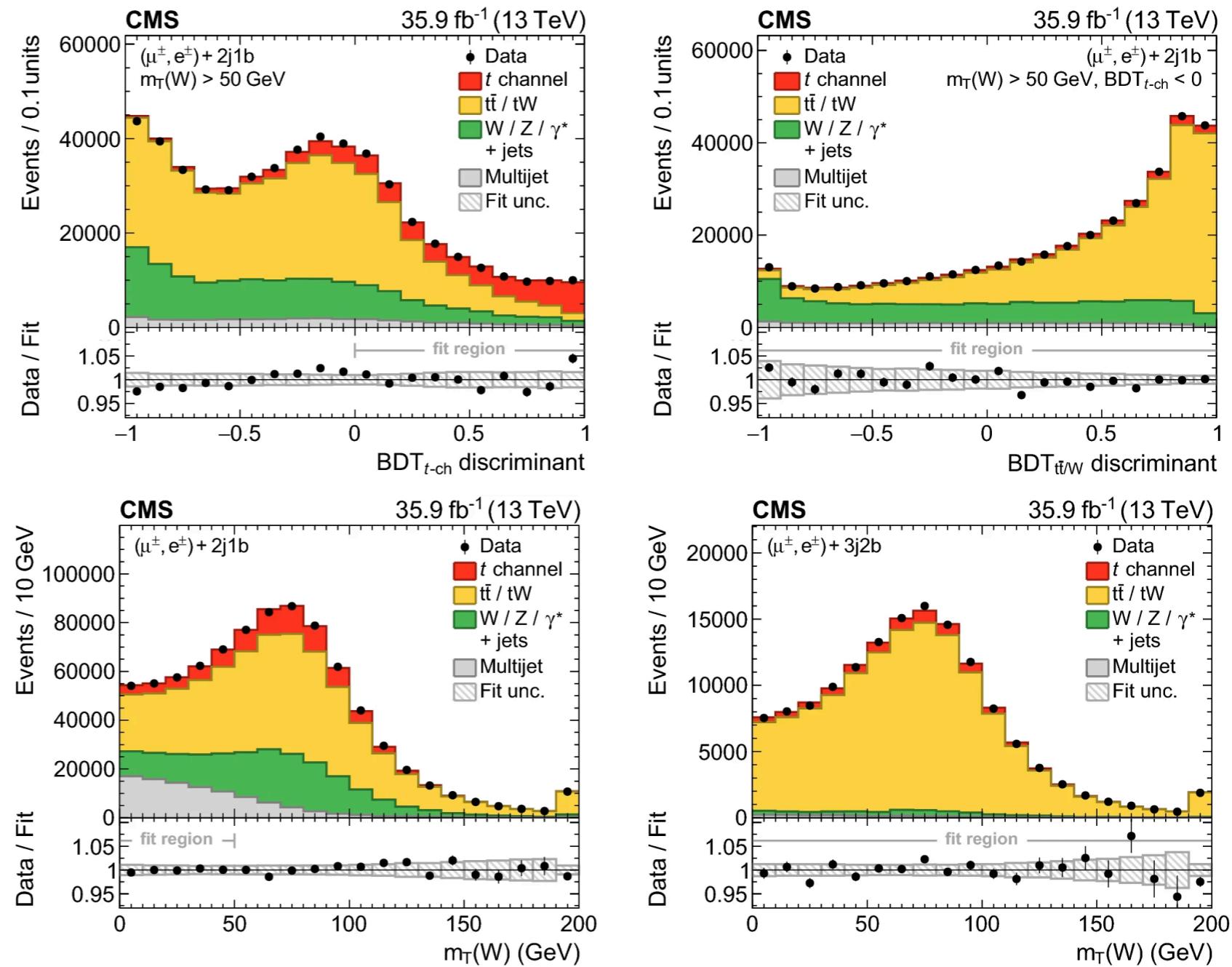
CMS t -CHANNEL DIFFERENTIAL CROSS-SECTION MEASUREMENTS

- Templates of the multijet background are estimated in sideband regions (w.r.t. 2j1b, 3j2b).
 - Muon isolation requirement inverted.
 - Selected electrons fail loose identification criteria.
- The normalisation is obtained directly in the fit to the data.
- The procedure is previously validated in the 2j0b region:



CMS t -CHANNEL DIFFERENTIAL CROSS-SECTION MEASUREMENTS

- The signal and background yields are estimated from a ML fit to the data:
 - $m_T(W)$ in the 2j1b region for $m_T(W) < 50$ GeV: Sensitive to multijet.
 - $m_T(W)$ in the 3j2b region: Sensitive to $t\bar{t}$.
 - $BDT_{t\text{-ch}}$ in the 2j1b region for $m_T(W) > 50$ GeV & $BDT_{t\text{-ch}} > 0$: Sensitive to t -channel signal.
 - $BDT_{t\bar{t}/W}$ in the 2j1b region for $m_T(W) > 50$ GeV & $BDT_{t\text{-ch}} < 0$: Sensitive to $W+jets$ and $t\bar{t}$.

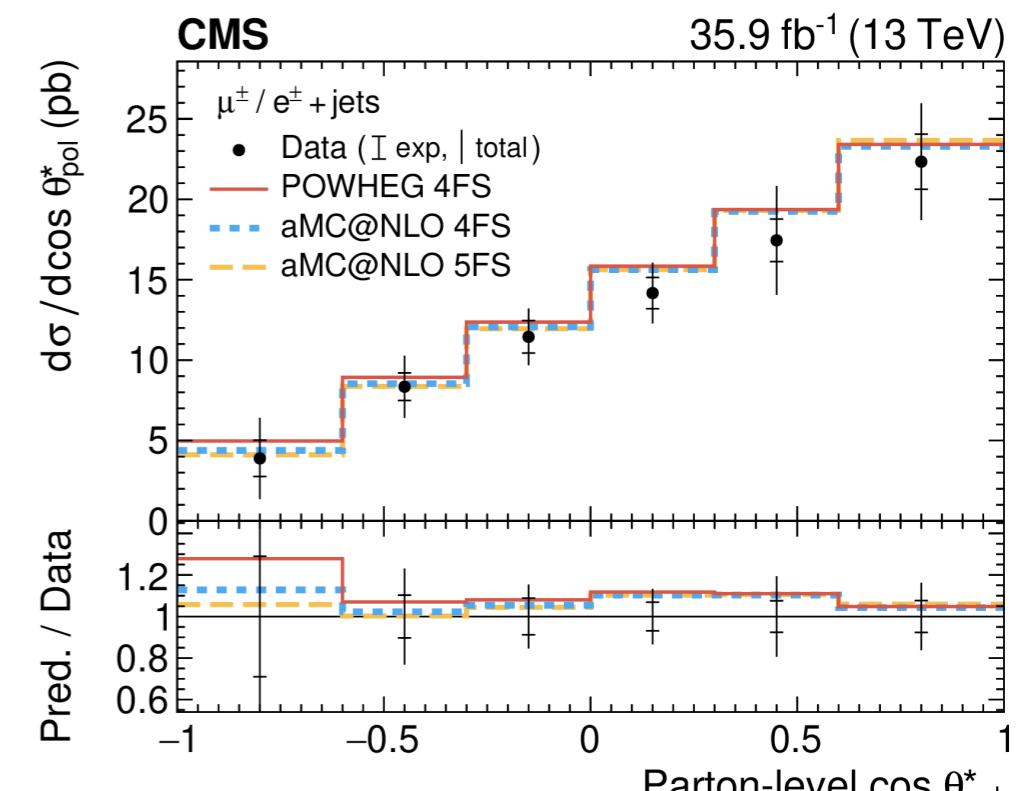


Process	μ^+	μ^-	e^+	e^-
$W/Z/\gamma^*+jets$	$72\,000 \pm 6\,800$	$62\,800 \pm 5\,600$	$33\,400 \pm 3\,200$	$30\,700 \pm 2\,800$
$t\bar{t}/tW$	$142\,400 \pm 2\,400$	$143\,400 \pm 2\,500$	$84\,500 \pm 1\,400$	$84\,800 \pm 1\,500$
Multijet	$35\,150 \pm 550$	$35\,710 \pm 760$	$13\,500 \pm 1\,000$	$12\,700 \pm 1\,000$
t channel (top quark)	$34\,400 \pm 1\,500$	10 ± 3	$17\,720 \pm 820$	27 ± 2
t channel (top antiquark)	13 ± 2	$21\,600 \pm 1\,600$	25 ± 3	$11\,460 \pm 880$
Total	$284\,100 \pm 5\,800$	$263\,700 \pm 4\,600$	$149\,300 \pm 2\,400$	$139\,700 \pm 2\,200$
Data	283 391	260 044	148 418	138 781

CMS t -CHANNEL DIFFERENTIAL CROSS-SECTION MEASUREMENTS

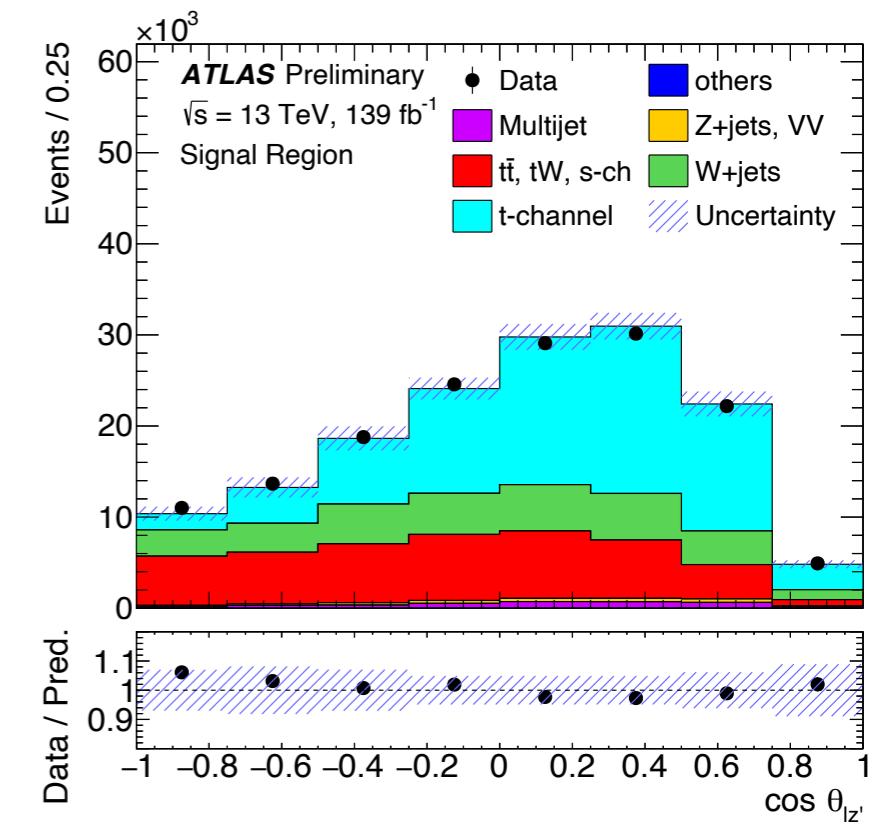
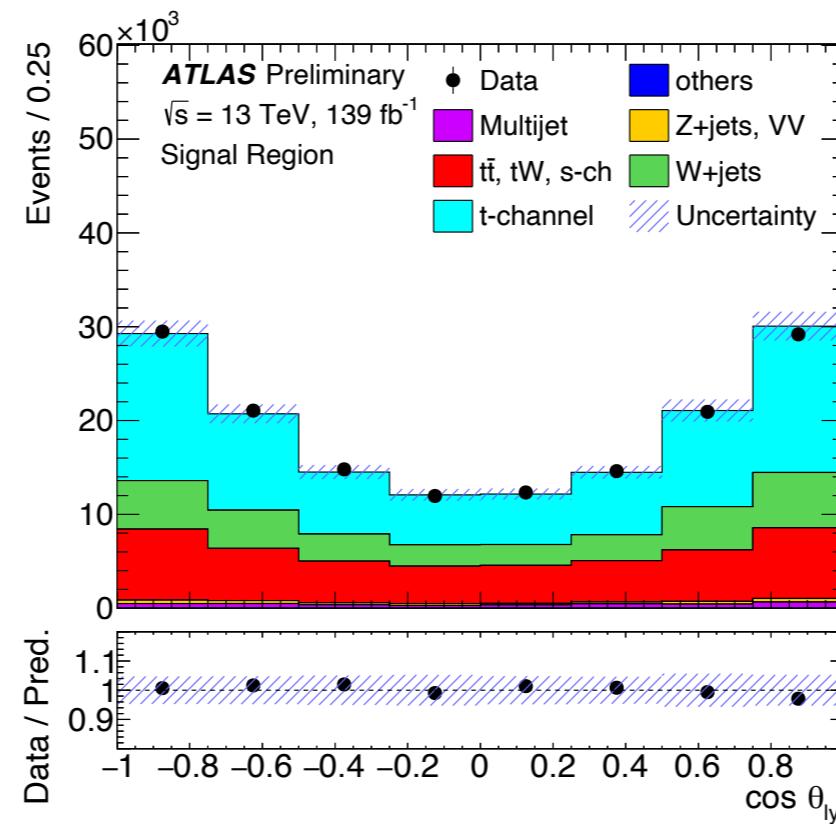
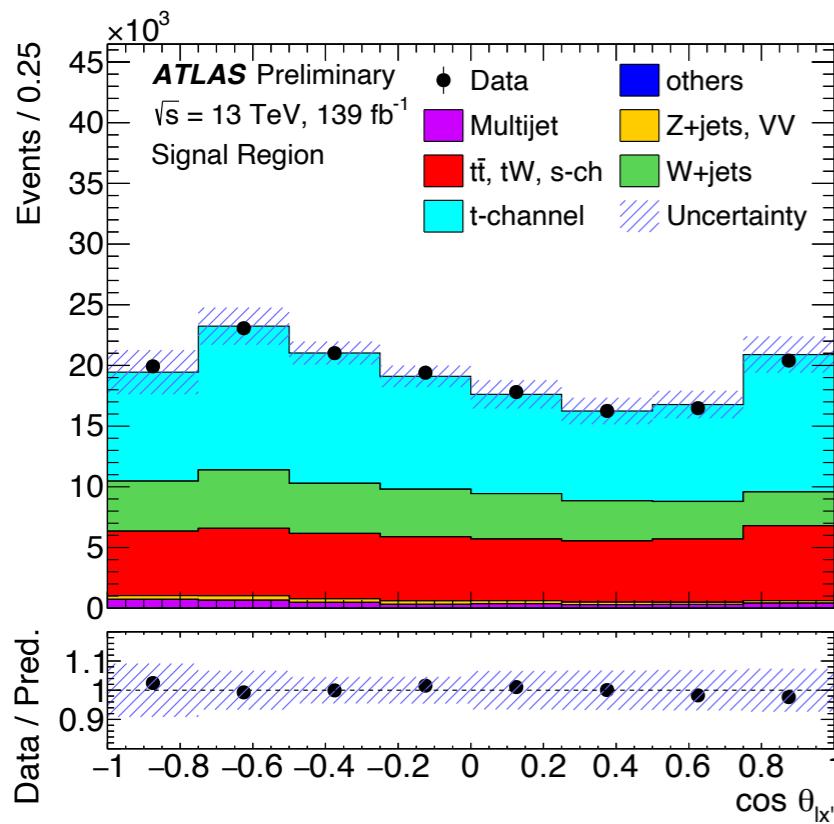
- Uncertainties breakdown in the spin asymmetry measurement:

	A_μ	A_e	$A_{\mu+e}$
Central values	0.403	0.446	0.440
Statistical	± 0.029	± 0.038	± 0.024
$t\bar{t}/tW$ normalisation	± 0.010	± 0.007	± 0.007
$W/Z/\gamma^*+$ jets normalisation	± 0.012	± 0.011	± 0.012
Multijet normalisation	<0.001	<0.001	± 0.003
Multijet shape	<0.001	± 0.006	<0.001
Jet energy scale/resolution	± 0.008	<0.001	<0.001
b tagging efficiencies/misidentification	<0.001	± 0.009	± 0.004
Others	<0.001	± 0.003	± 0.005
Top quark mass	± 0.033	± 0.063	± 0.044
PDF+ α_S	± 0.011	± 0.009	± 0.011
t channel renorm./fact. scales	± 0.013	± 0.018	± 0.020
t channel parton shower	± 0.030	± 0.008	± 0.014
$t\bar{t}$ renorm./fact. scales	± 0.008	± 0.019	± 0.017
$t\bar{t}$ parton shower	± 0.031	± 0.037	± 0.033
$t\bar{t}$ underlying event tune	<0.001	± 0.014	± 0.014
$t\bar{t} p_T$ reweighting	<0.001	± 0.010	± 0.009
$W+$ jets renorm./fact. scales	<0.001	± 0.019	± 0.014
Color reconnection	± 0.036	± 0.056	± 0.031
Fragmentation model	± 0.011	± 0.011	± 0.011
Profiled uncertainties only (statistical+experimental)	± 0.041	± 0.047	± 0.031
Total uncertainties	± 0.071	± 0.099	± 0.070



ATLAS TOP QUARK POLARISATION

- **Normalised differential cross-section measurements:**
 - The normalisations of the W+jets and top-quark backgrounds and the t -channel signal are constrained with a maximum likelihood fit to the data in the signal and control regions.
 - After background subtraction the distributions are unfolded to the particle-level in a fiducial region



ATLAS TOP QUARK POLARISATION

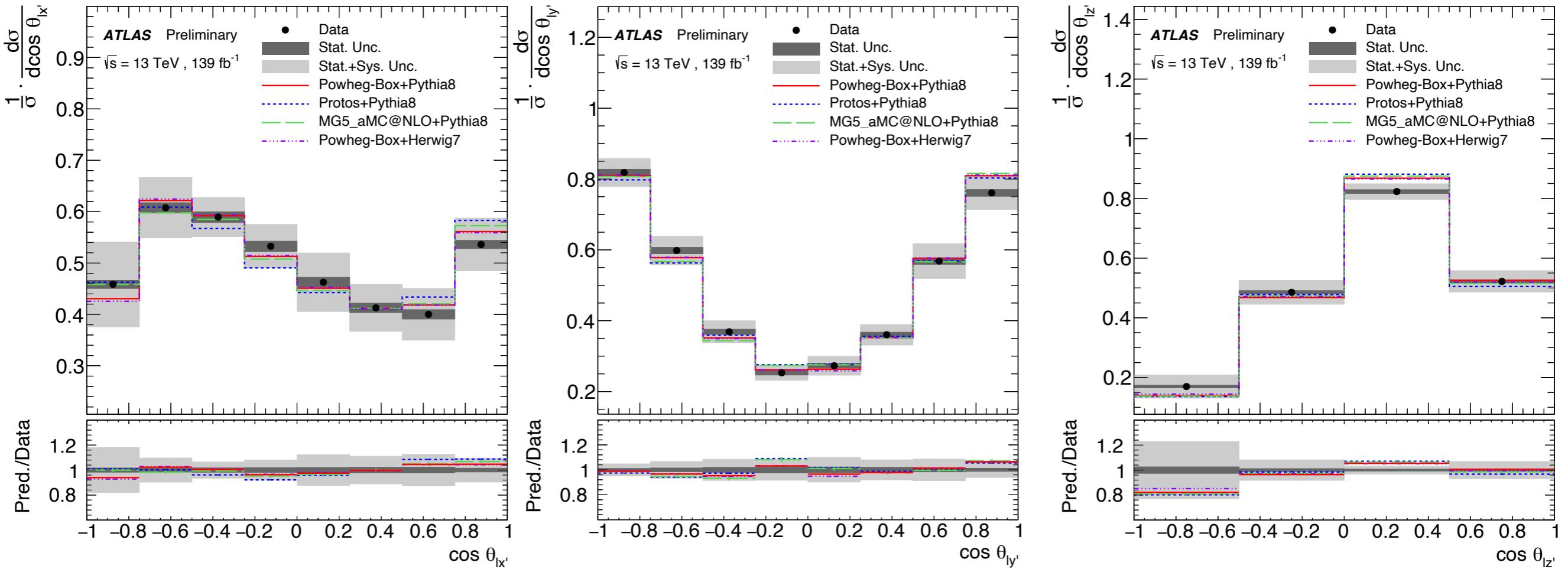
- **Normalised differential cross-section measurements:**
 - An iterative Bayesian approach implemented in RooUnfold is used with additional correction factors.
 - The correction factors and unfolding matrices are computed using t-channel single top events generated with Powheg+Pythia 8 at NLO.
 - 8 bins used for θ_X and θ_Y , 4 bins used for θ_Z (ensure $> 70\%$ of events in diagonal elements of the migration matrix and not a very large number of iterations).
 - Convergence, closure and linearity tests have been performed.

$$\nu_k^{\text{particle}} = C_k^{\text{particle!reco}} \sum_j M_{jk}^{-1} C_j^{\text{reco!particle}} (N_j^{\text{data}} - B_j),$$

$$C_j^{\text{reco!particle}} = \frac{S_j^{\text{reco}} - S_j^{\text{reco!particle}}}{S_j^{\text{reco}}},$$

$$C_k^{\text{particle!reco}} = \frac{1}{\epsilon_k} = \frac{S_k^{\text{particle}}}{S_k^{\text{particle}} - S_k^{\text{particle!reco}}},$$

ATLAS TOP QUARK POLARISATION



Angular variable	χ^2/NDF	$p\text{-value}$
$\cos \theta_{lx'}$	1.53/7	0.98
$\cos \theta_{ly'}$	4.25/7	0.75
$\cos \theta_{lz'}$	2.98/3	0.39

ATLAS TOP QUARK POLARISATION

- Deviations from SM predictions of the differential measurements can give hints of physics beyond the SM (the measurement can be interpreted within an EFT framework in terms of tWb anomalous couplings or Wilson coefficients).
- In an EFT framework:

$$\mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i^{[6]} + \text{hermitian conjugate}$$

- In single-top t-channel production (for massless b-quarks) at LO QCD and at $\mathcal{O}(1/\Lambda^2)$, only three operators with three coefficients are required to parametrize new physics effects:

$$\begin{aligned} O_{\varphi Q}^{(3)} &= i \frac{1}{2} y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu^I \varphi \right) (\bar{Q} \gamma^\mu \tau^I Q) \\ O_{tW} &= y_t g_w (\bar{Q} \sigma^{\mu\nu} \tau^I t) \tilde{\varphi} W_{\mu\nu}^I \\ O_{qQ,rs}^{(3)} &= (\bar{q}_r \gamma^\mu \tau^I q_s) (\bar{Q} \gamma_\mu \tau^I Q) \end{aligned}$$

- In terms of anomalous couplings, the most general effective tWb interaction arising from a minimal set of dimension-six effective operators was found to be:

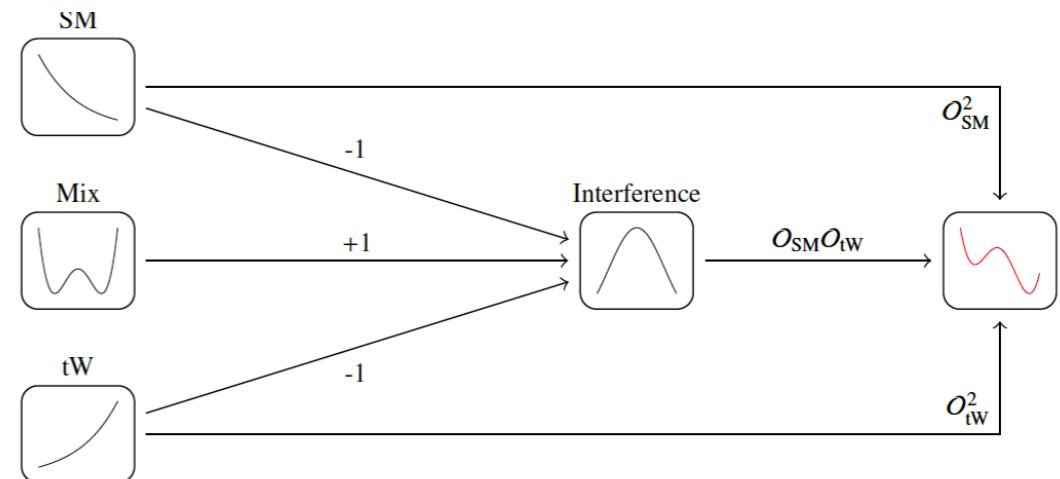
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i \sigma^{\mu\nu} q_\nu}{m_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.} \quad g_R = \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2},$$

ATLAS TOP QUARK POLARISATION

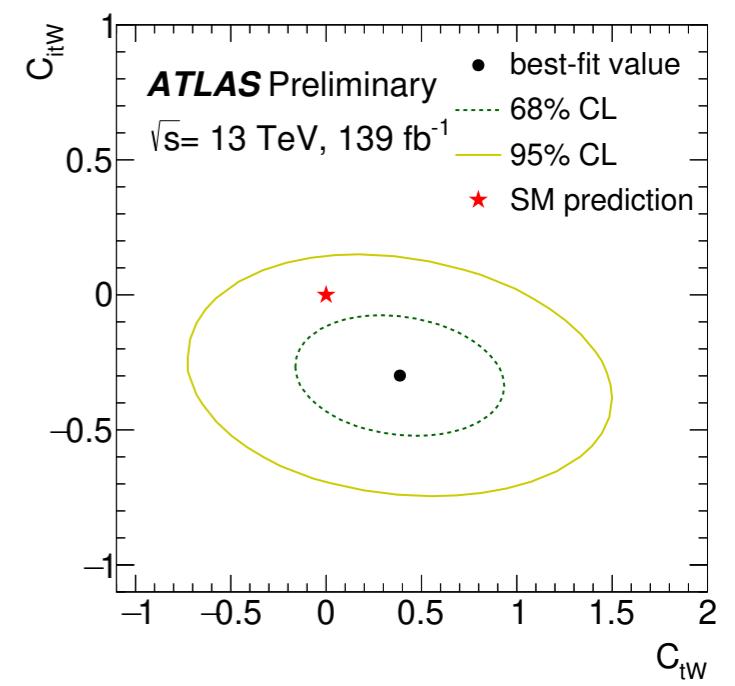
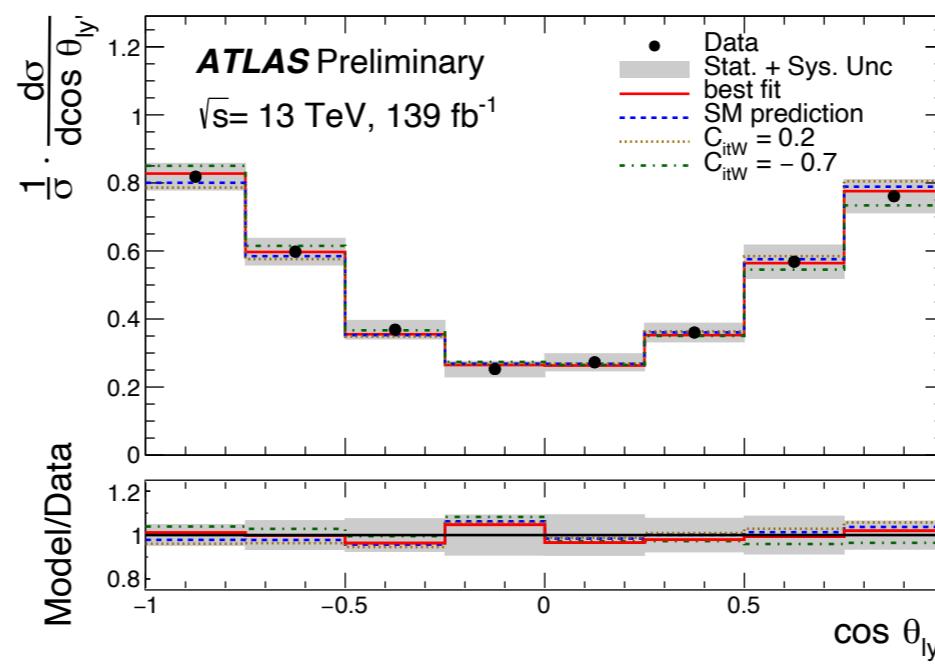
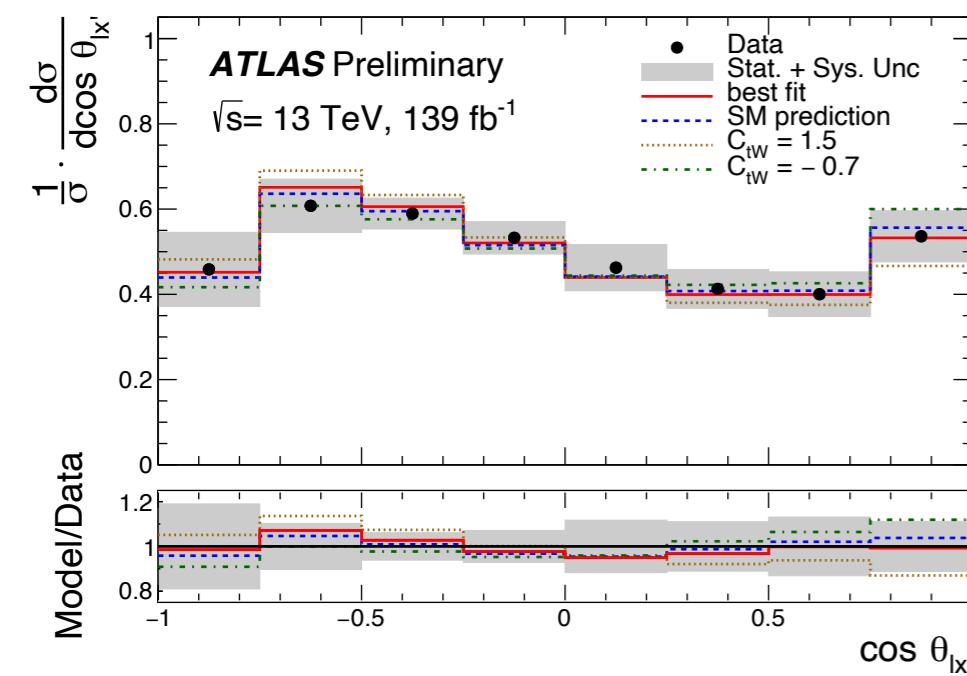
- A set of morphing templates are used to simulate the SM, the interference and the pure BSM terms.

$$\sigma(c_{tW}, c_{itW}) = \left| \mathcal{O}_{SM} + c_{tW} \cdot \mathcal{O}_{tW} + c_{itW} \cdot \mathcal{O}_{itW} \right|_{\text{production}}^2 \cdot \left| \mathcal{O}_{SM} + c_{tW} \cdot \mathcal{O}_{tW} + c_{itW} \cdot \mathcal{O}_{itW} \right|_{\text{decay}}^2$$

- All orders in Λ are included.
- A total of 15 templates are used.



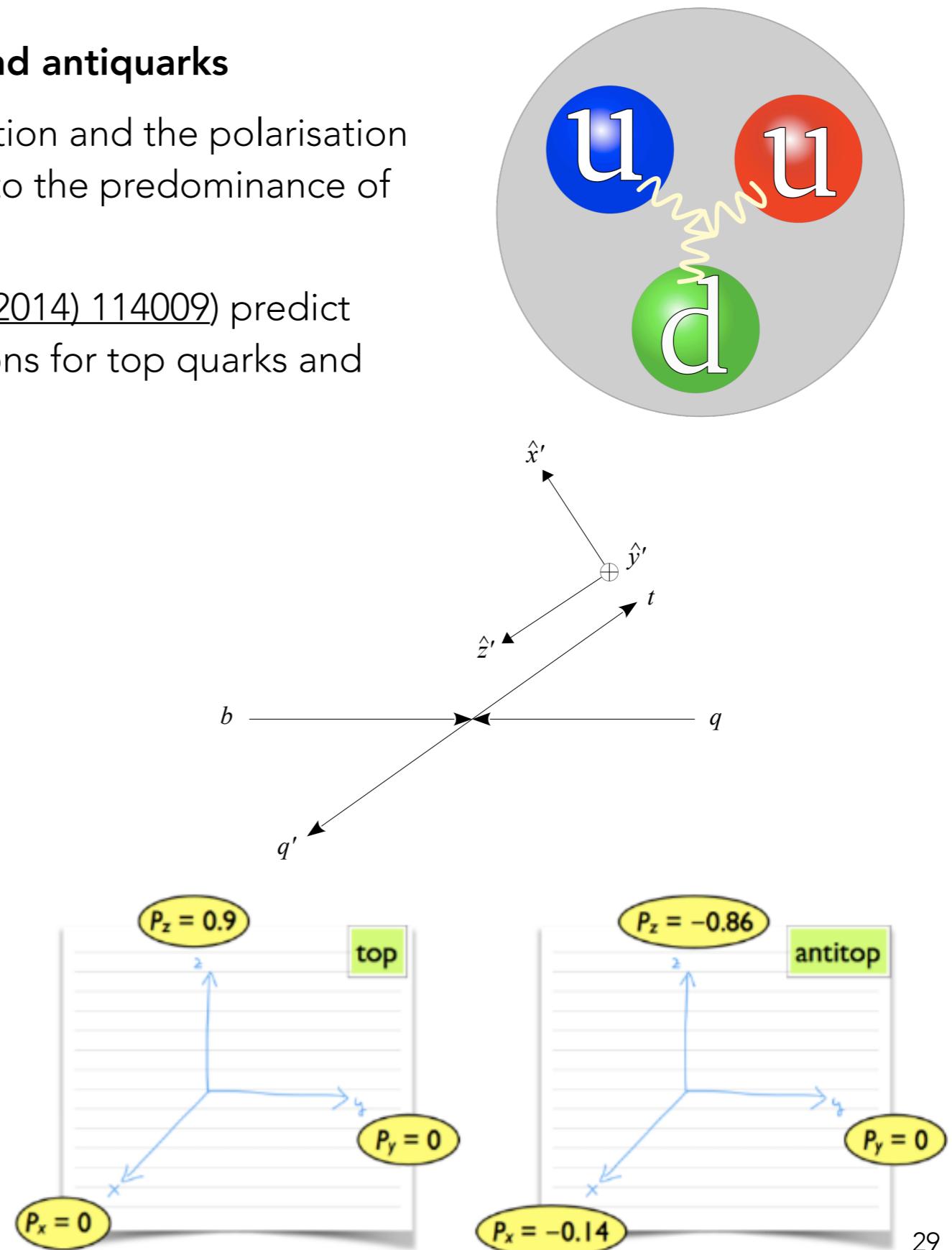
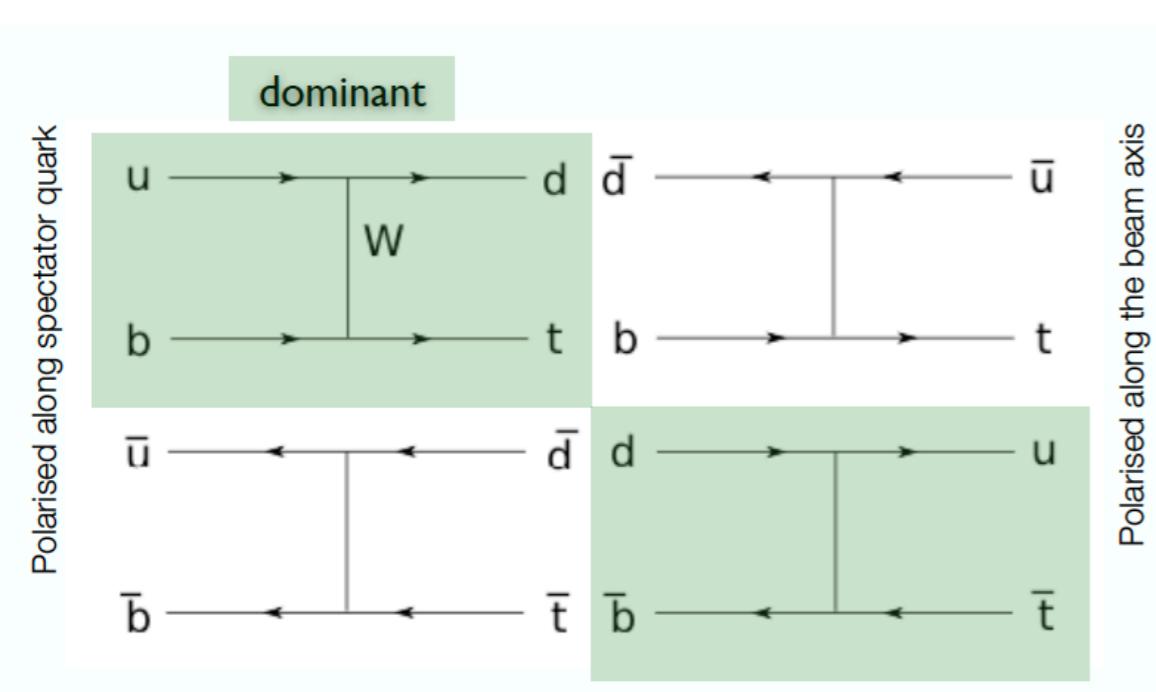
- A maximum likelihood fit is performed to the unfolded differential cross-section measurements to extract the EFT predictions.



ATLAS TOP QUARK POLARISATION

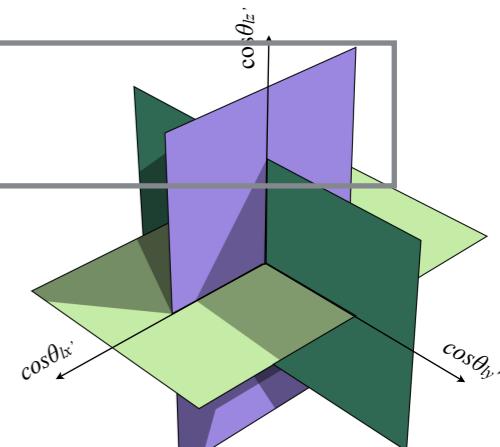
Differential measurements for top quarks and antiquarks

- In pp collisions, both the production cross-section and the polarisation of top quarks and top antiquarks differ owing to the predominance of u-type quarks in the proton.
- Theoretical predictions at LO ([Phys. Rev. D89 \(2014\) 114009](#)) predict different polarisations in the different projections for top quarks and antiquarks.



ATLAS TOP QUARK POLARISATION

- The portion μ of the fitting function describes the expected number of events as a function of the octant variable is given by:



$$\mu(Q_{\pm}; \vec{P}, \vec{\beta}, \vec{\theta}) = \beta_{t\text{-channel}} \cdot \left\{ \frac{1+P_z}{2} \mathcal{T}_{z+}(Q_{\pm}) + \frac{1-P_z}{2} \mathcal{T}_{z-}(Q_{\pm}) + \frac{P_x}{2} \mathcal{T}_x(Q_{\pm}) + \frac{P_y}{2} \mathcal{T}_y(Q_{\pm}) \right\} + \mathcal{T}_{\text{bkg}}(Q_{\pm}, \beta_{W+\text{jets}}, \beta_{t\bar{t}})$$

Lepton sign

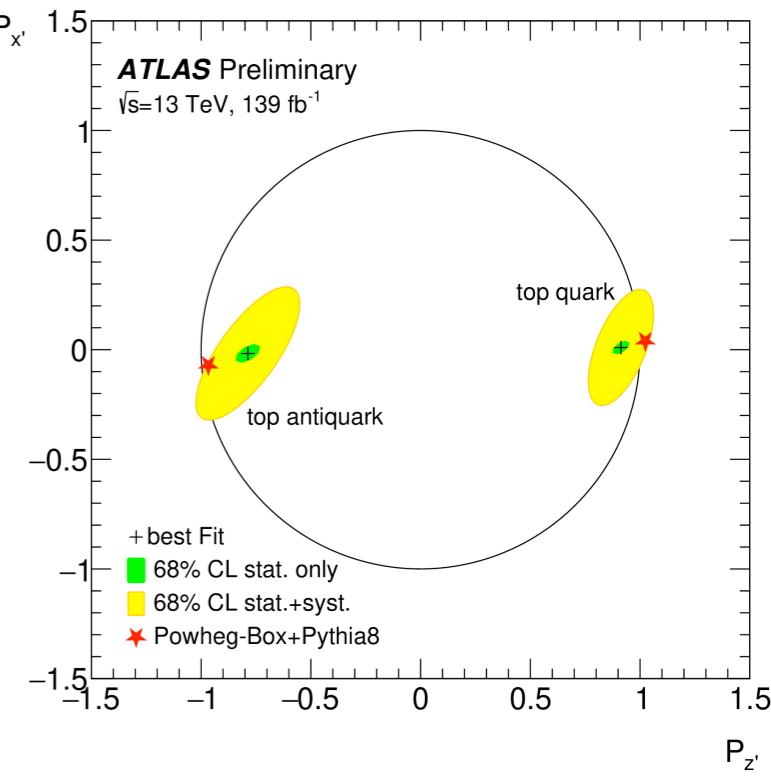
Fully polarised templates

$$Q = 4 \cdot \Theta(\cos \theta_{\ell z'}) + 2 \cdot \Theta(\cos \theta_{\ell x'}) + \Theta(\cos \theta_{\ell y'})$$

- The fitting functions is used in the maximisation of the likelihood function:

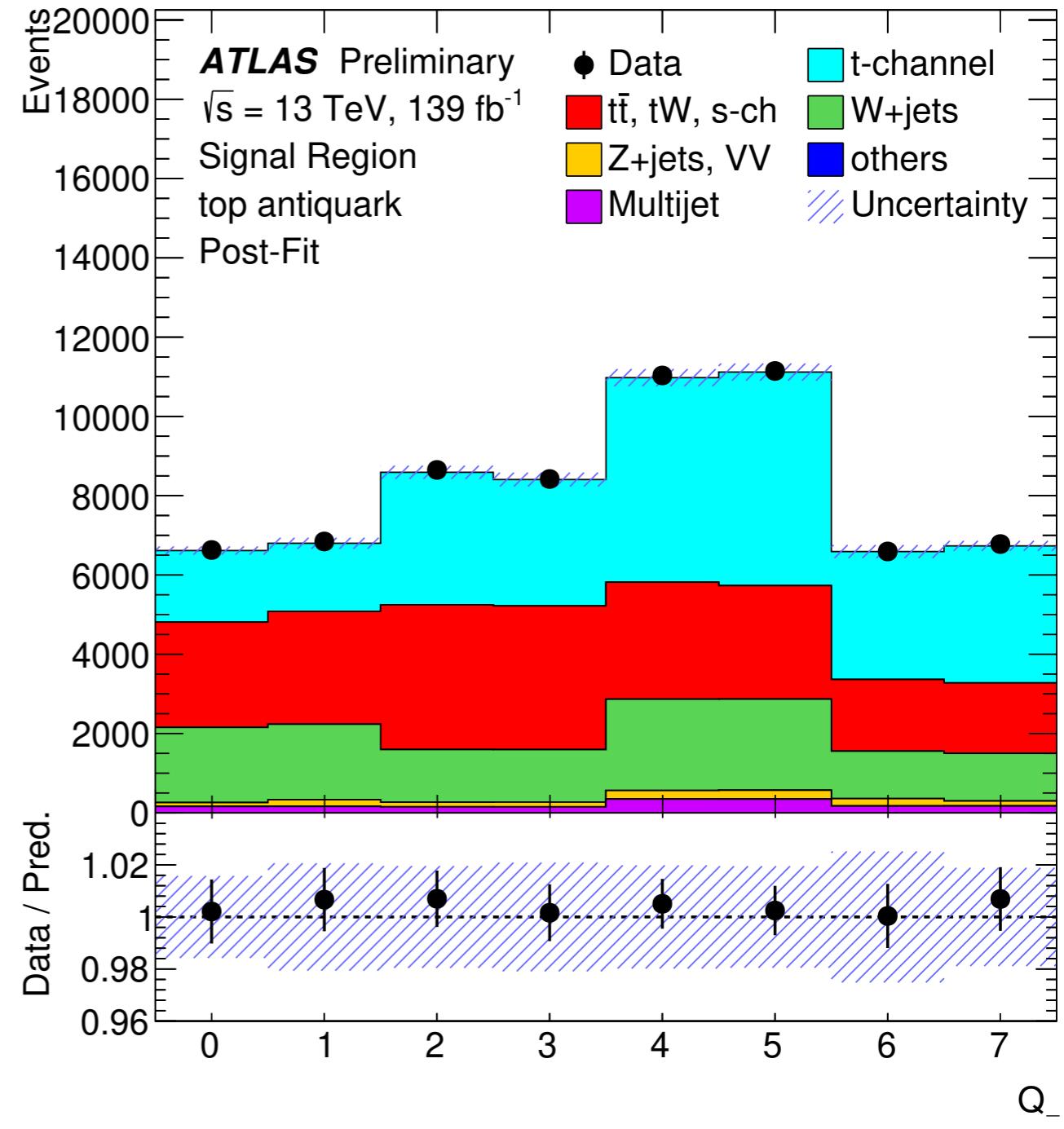
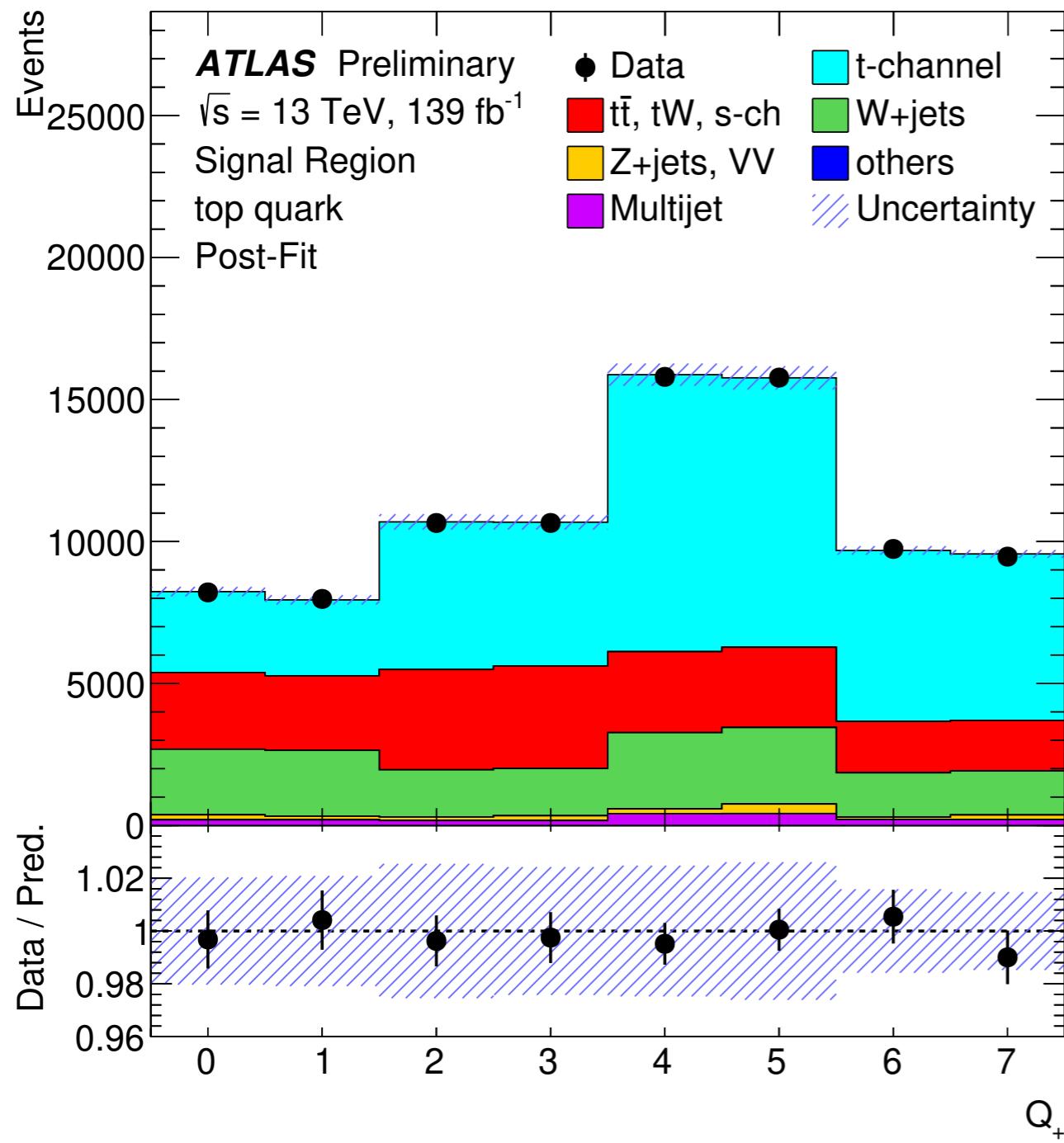
$$\begin{aligned} \mathcal{L}(\vec{\mathcal{P}}, \vec{\beta}, \vec{\theta}) &= \prod_{Q_+=1}^8 \mathcal{P}\left(N_{Q_+}; \mu\left(Q_+; \vec{P}, \vec{\beta}, \vec{\theta}\right)\right) \prod_{Q_-=1}^8 \mathcal{P}\left(N_{Q_-}; \mu\left(Q_-; \vec{P}, \vec{\beta}, \vec{\theta}\right)\right) \longrightarrow \text{Signal regions} \\ &\times \prod_{j_+=1}^2 \mathcal{P}\left(N_{j_+}; \nu\left(j_+; \vec{\beta}, \vec{\theta}\right)\right) \prod_{j_-=1}^2 \mathcal{P}\left(N_{j_-}; \nu\left(j_-; \vec{\beta}, \vec{\theta}\right)\right) \longrightarrow \text{Control regions} \\ &\times \prod_{k=1}^3 \mathcal{G}(\beta_k; 1, \sigma_k), \times \prod_l G(\theta_l; 0, 1) \longrightarrow \text{Gaussian constraints} \end{aligned}$$

- The results of the polarisation vectors are in agreement with the SM predictions.



ATLAS TOP QUARK POLARISATION

- Template-fit distributions of the octant variables for both top quarks and antiquarks:



ATLAS TOP QUARK POLARISATION

- Event selection in the signal and the control regions:

Preselection region	Signal region	$t\bar{t}$ control region	$W+jets$ control region
	$=1$ charged tight lepton ($p_T > 30$ GeV and $ \eta < 2.5$) Veto secondary low- p_T charged loose leptons ($p_T > 10$ GeV and $ \eta < 2.5$) $=2$ jets ($p_T > 30$ GeV and $ \eta < 4.5$; $p_T > 35$ GeV within $2.7 < \eta < 3.5$) $E_T^{\text{miss}} > 35$ GeV $m_T(\ell E_T^{\text{miss}}) > 60$ GeV $p_T(\ell) > 50 \left(1 - \frac{\pi - \Delta\phi(j_1, \ell) }{\pi - 1}\right)$ GeV		
	$=1$ b -jet ($ \eta < 2.5$; 60%WP) $m_{\ell b} < 153$ GeV $m_{\ell E_T^{\text{miss}} b} \in [120.6, 234.6]$ GeV trapez. requirement $m_{j\ell E_T^{\text{miss}} b} > 320$ GeV $H_T > 190$ GeV	$=2$ b -jet ($ \eta < 2.5$; 60%WP)	$=1$ b -jet ($ \eta < 2.5$; 60%WP) $m_{\ell b} > 153$ GeV $m_{\ell E_T^{\text{miss}} b} \notin [120.6, 234.6]$ GeV veto trapez. requirement $m_{j\ell E_T^{\text{miss}} b} < 320$ GeV $H_T < 190$ GeV

Process	Preselection region	Signal region	$t\bar{t}$ control region	$W+jets$ control region
t -channel	$219\,000 \pm 11\,000$	$70\,600 \pm 3\,500$	$13\,480 \pm 680$	$148\,200 \pm 7\,400$
$t\bar{t}$, tW , s -channel	$736\,000 \pm 39\,000$	$43\,200 \pm 2\,400$	$147\,800 \pm 8\,400$	$693\,000 \pm 37\,000$
$W+jets$	$590\,000 \pm 200\,000$	$26\,200 \pm 8\,900$	$16\,100 \pm 5\,500$	$560\,000 \pm 190\,000$
$Z+jets$, diboson	$52\,900 \pm 5\,100$	$2\,120 \pm 350$	$2\,620 \pm 360$	$50\,800 \pm 4\,900$
Others	494 ± 38	30 ± 4	79 ± 6	464 ± 36
Multijet	$52\,000 \pm 10\,000$	$3\,500 \pm 640$	$5\,500 \pm 1\,800$	$48\,500 \pm 9\,400$
Total expected	$1650\,000 \pm 210\,000$	$145\,600 \pm 9\,900$	$186\,000 \pm 10\,000$	$1\,510\,000 \pm 200\,000$
Data	1 750 918	154 361	188 326	1 596 557
S/B	0.15 ± 0.02	0.94 ± 0.13	0.08 ± 0.01	0.11 ± 0.02
Data/Prediction	1.06 ± 0.13	1.06 ± 0.07	1.02 ± 0.06	1.06 ± 0.14

TOP QUARK POLARISATION: ATLAS AND CMS

- CMS provides a measurement of the spin asymmetry, sensitive to the top quark polarisation.

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_{\text{pol}}^*} = \frac{1}{2} \left(1 + 2A_\ell \cos \theta_{\text{pol}}^* \right), \quad A_\ell = \frac{1}{2} P \alpha_\ell \quad \cos \theta_{\text{pol}}^* = \frac{\vec{p}_{q'}^* \cdot \vec{p}_\ell^*}{|\vec{p}_{q'}^*| |\vec{p}_\ell^*|}$$

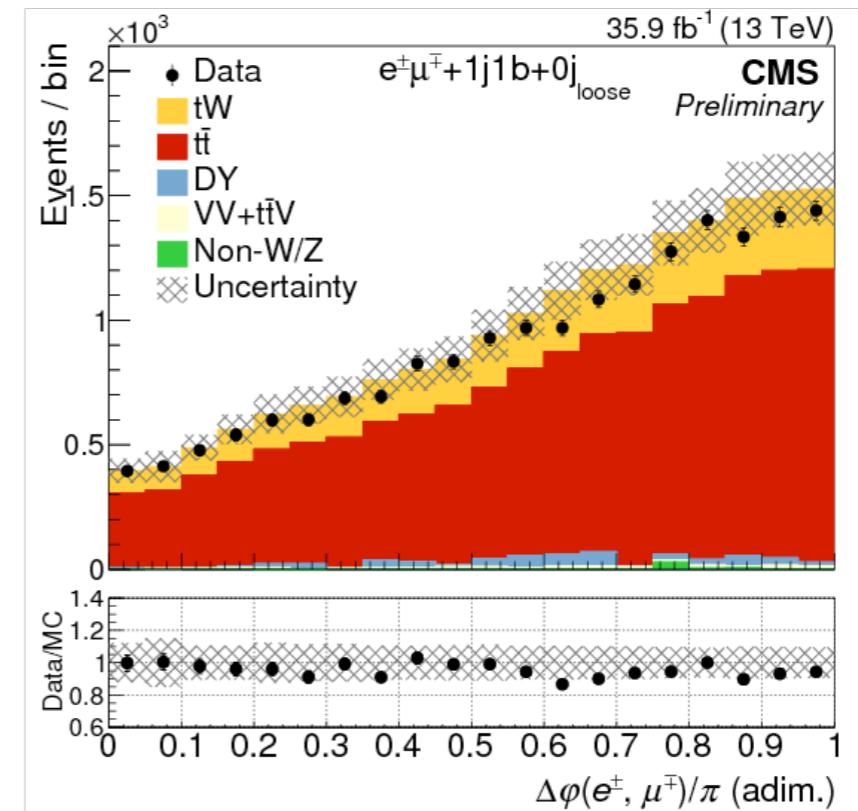
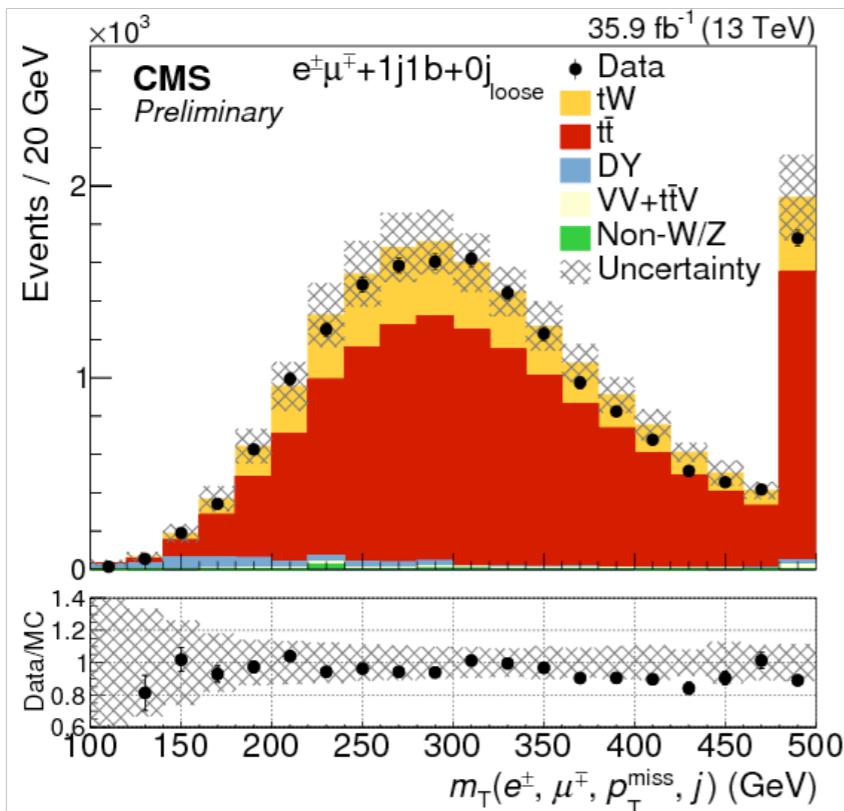
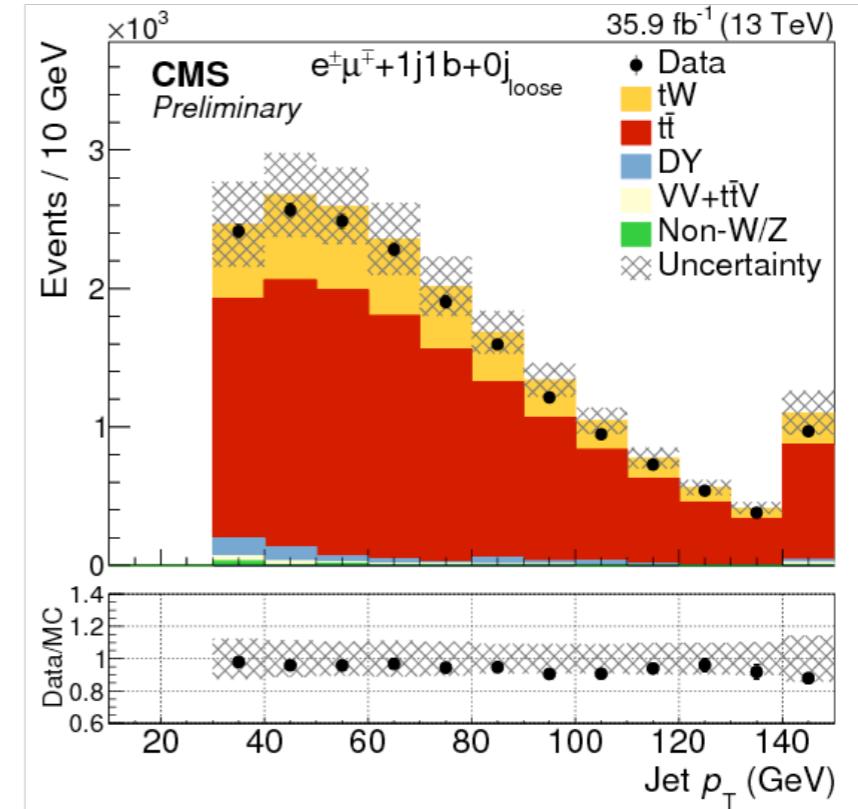
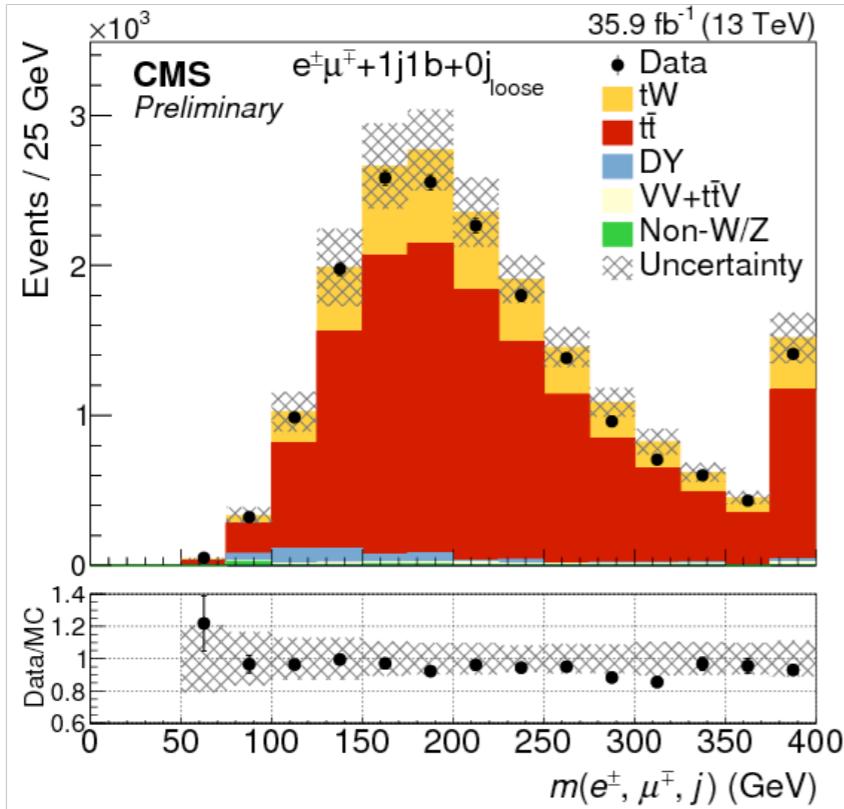
*top quark rest frame

- Measurement performed in the electron/muon/combined channels:
 - Combined channel: $A_l = 0.440 \pm 0.070$ ($\sigma_r \approx 16\%$).
- ATLAS provides a measurement of the polarisation vector for top quarks and antiquarks.
- The spin asymmetry can be related with the P_z components of the polarisation vectors.
 - The value reported by CMS is inclusive for top quarks and antiquarks.

Parameter	Extracted value	(stat.)
t -channel norm.	$+1.045 \pm 0.022$	(± 0.006)
$W + \text{jets}$ norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P_{x'}^t$	$+0.01 \pm 0.18$	(± 0.02)
$P_{x'}^{\bar{t}}$	-0.02 ± 0.20	(± 0.03)
$P_{y'}^t$	-0.029 ± 0.027	(± 0.011)
$P_{y'}^{\bar{t}}$	-0.007 ± 0.051	(± 0.017)
$P_{z'}^t$	$+0.91 \pm 0.10$	(± 0.02)
$P_{z'}^{\bar{t}}$	-0.79 ± 0.16	(± 0.03)

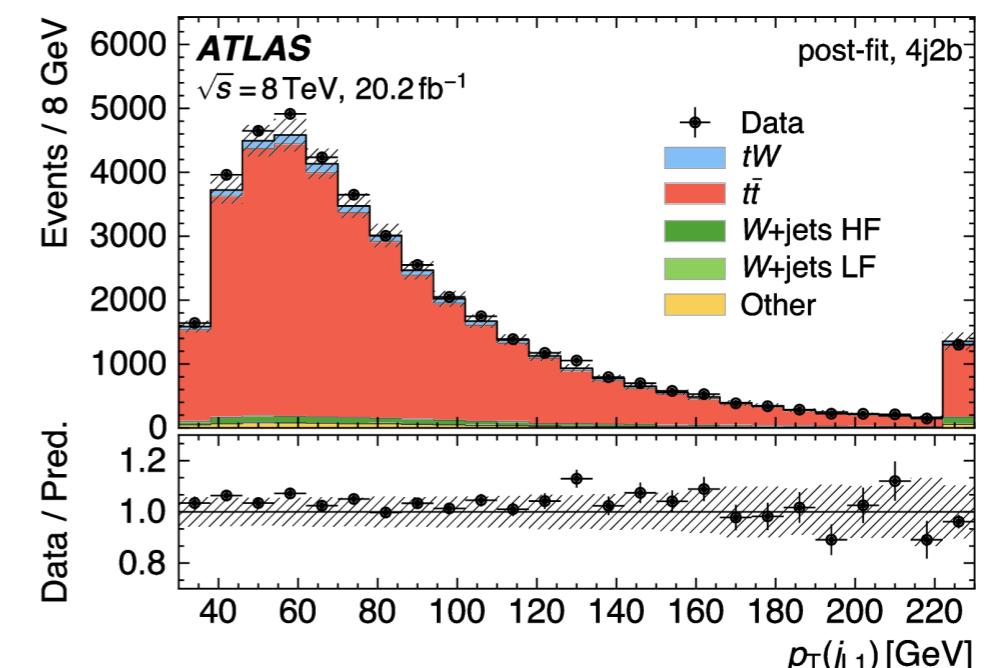
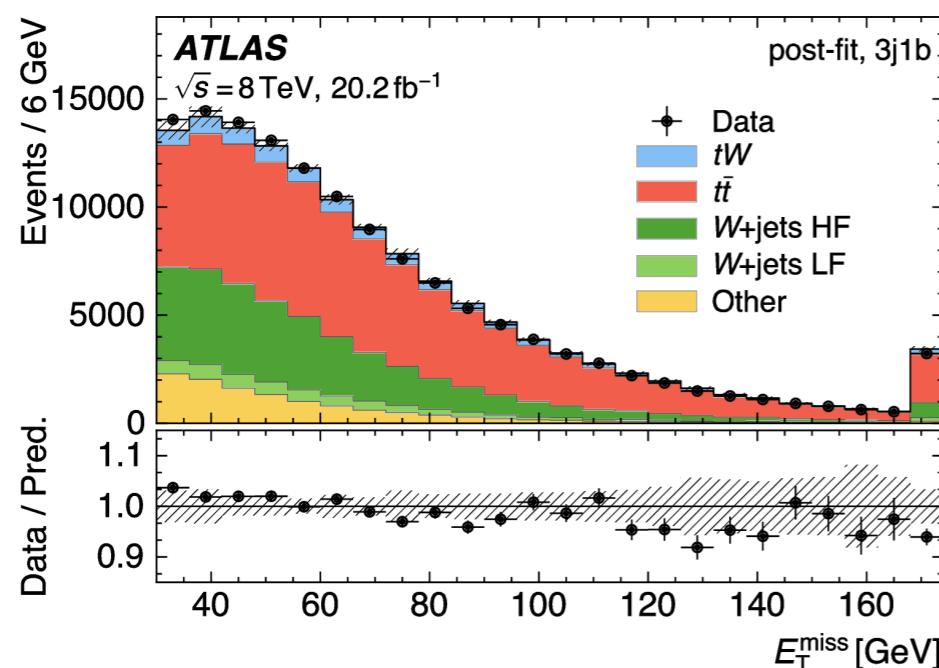
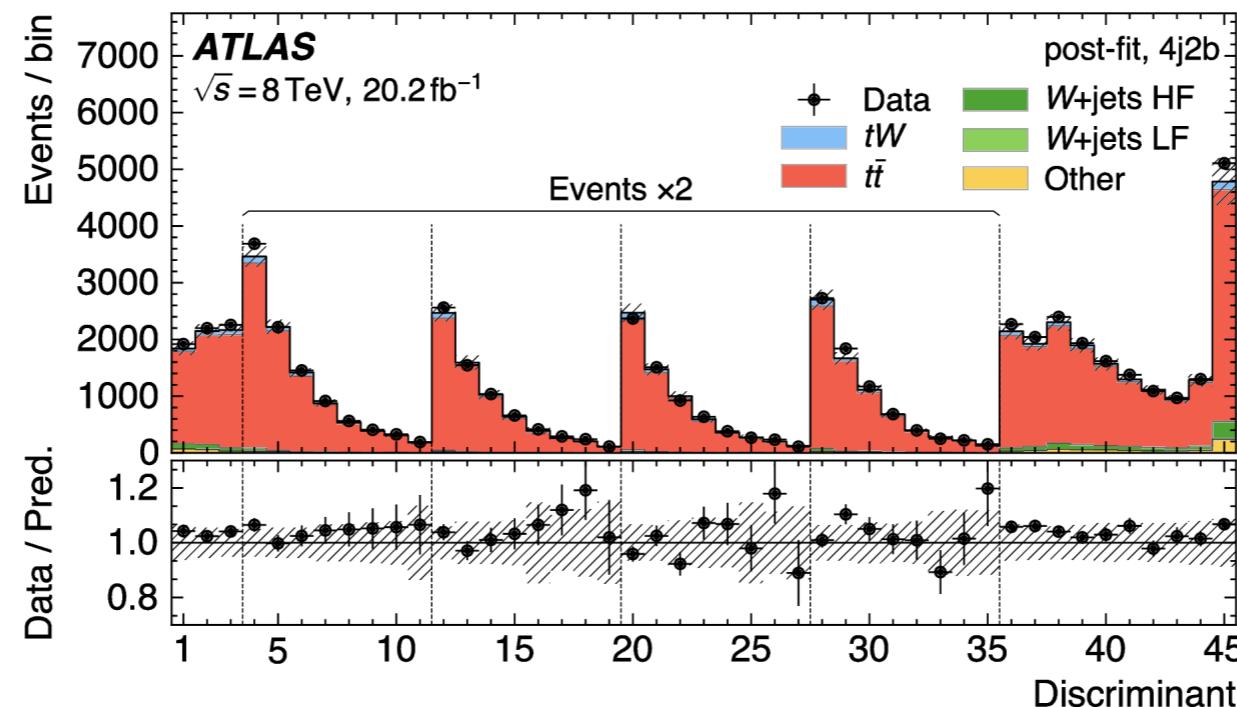
CMS tW DIFFERENTIAL CROSS-SECTION MEASUREMENTS

- Nice agreement between the data and the SM predictions prior to the unfolding procedure:



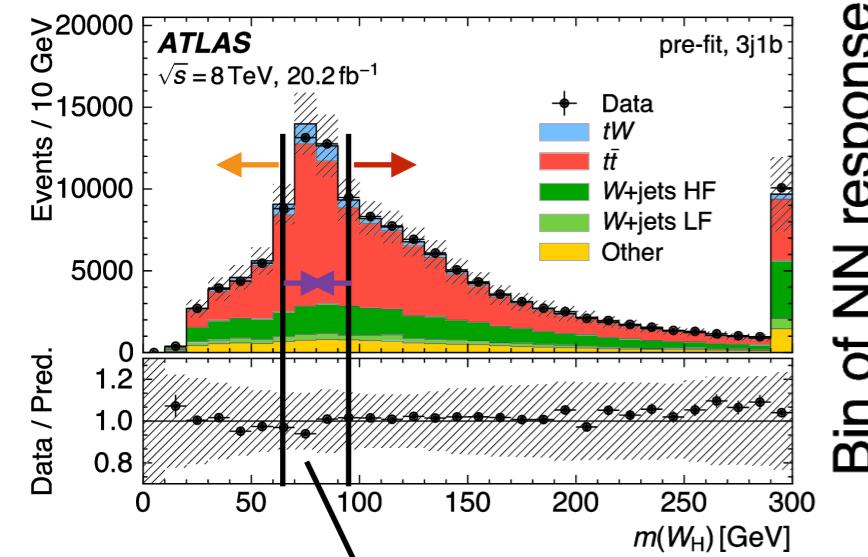
ATLAS tW CROSS-SECTION MEASUREMENT

- The fit results are validated in the signal and the $t\bar{t}$ VR.
- The expected distributions match the observed data in both regions.

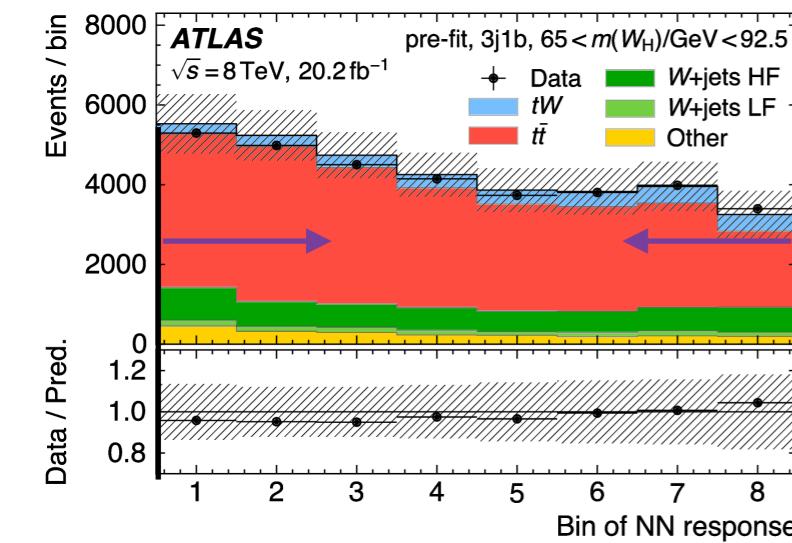


ATLAS tW CROSS-SECTION MEASUREMENT

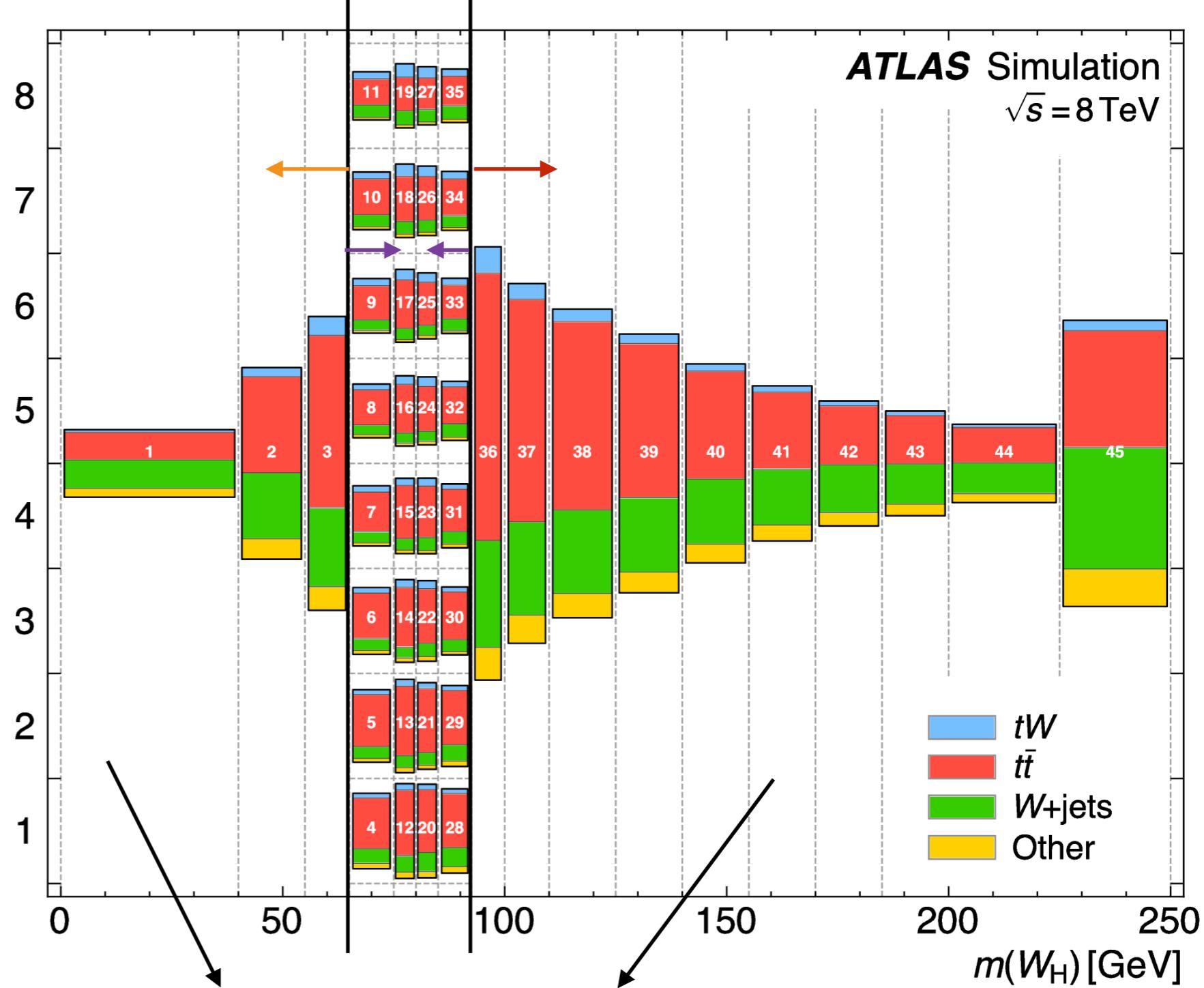
- The 2D discriminant is built from the $m(W_H)$ and the NN response:



NN trained in the peak region



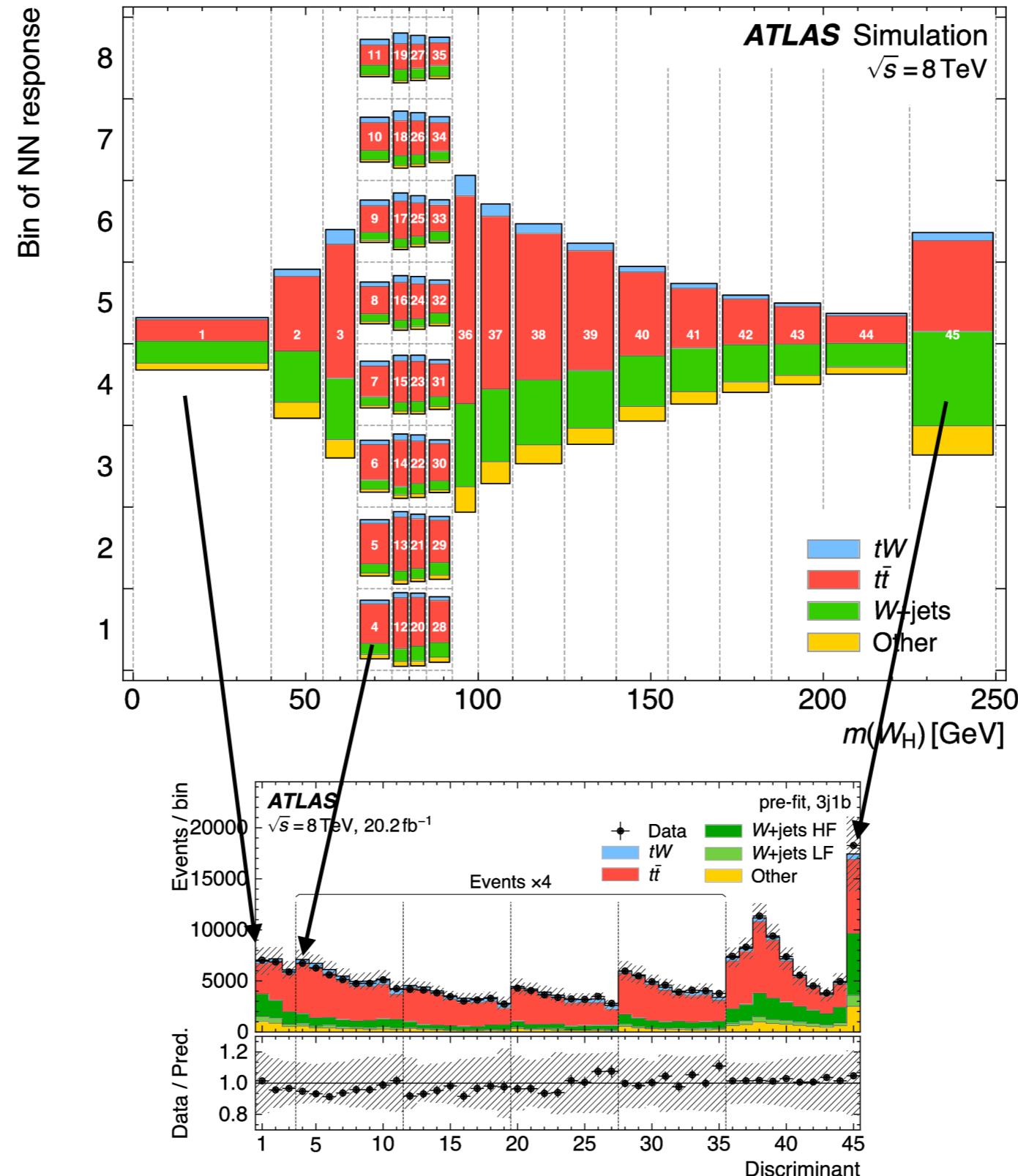
Inside the peak, each bin in the y axis corresponds to a bin of the NN response



Outside the peak region, the NN bins are merged

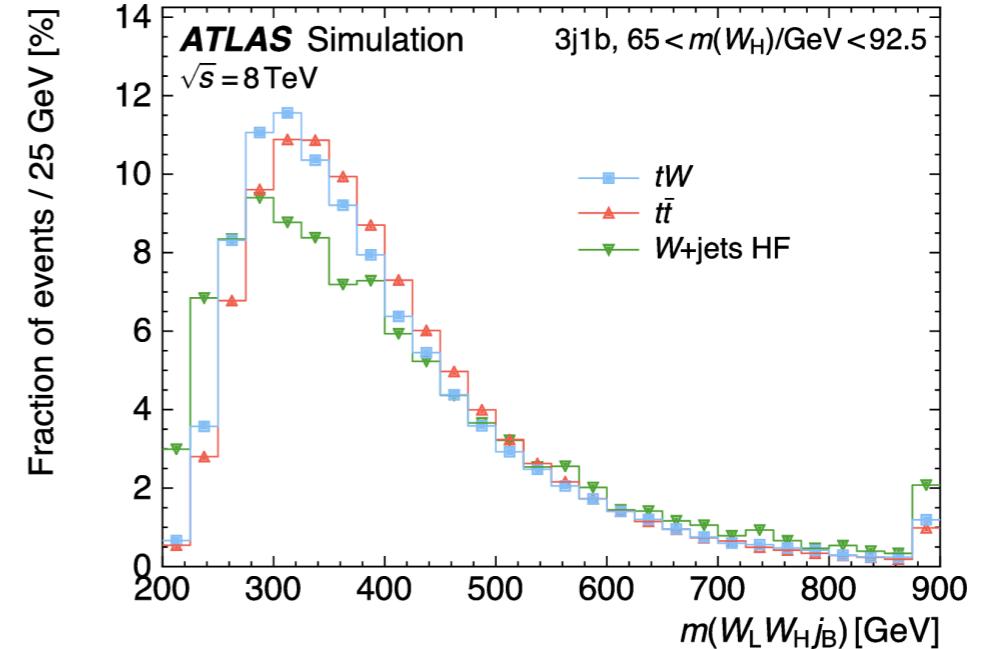
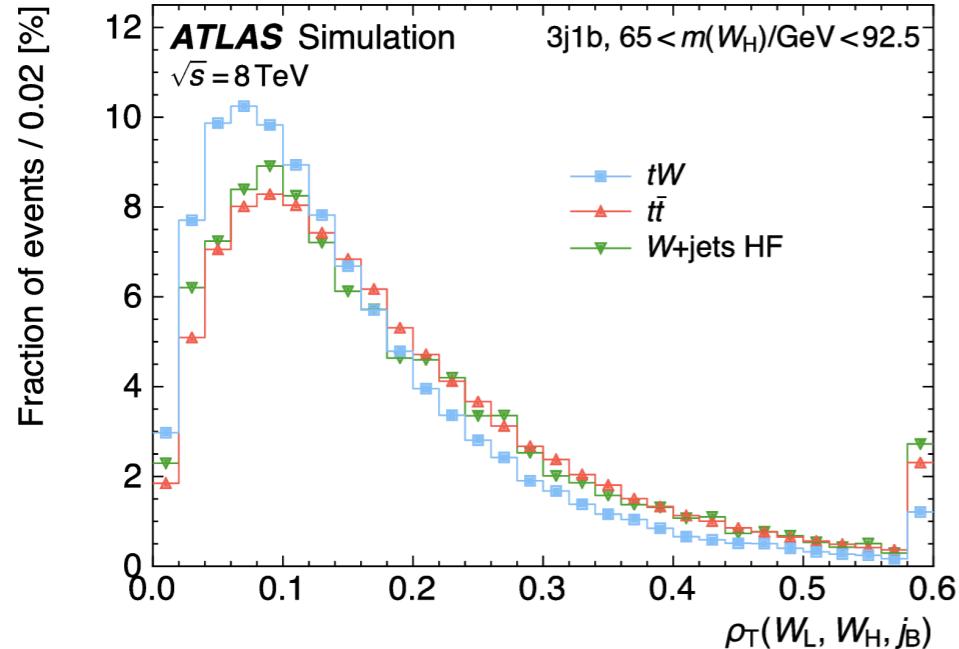
ATLAS tW CROSS-SECTION MEASUREMENT

- Each white number in the 2D discriminant corresponds to a bin in the 1D histogram.



ATLAS tW CROSS-SECTION MEASUREMENT

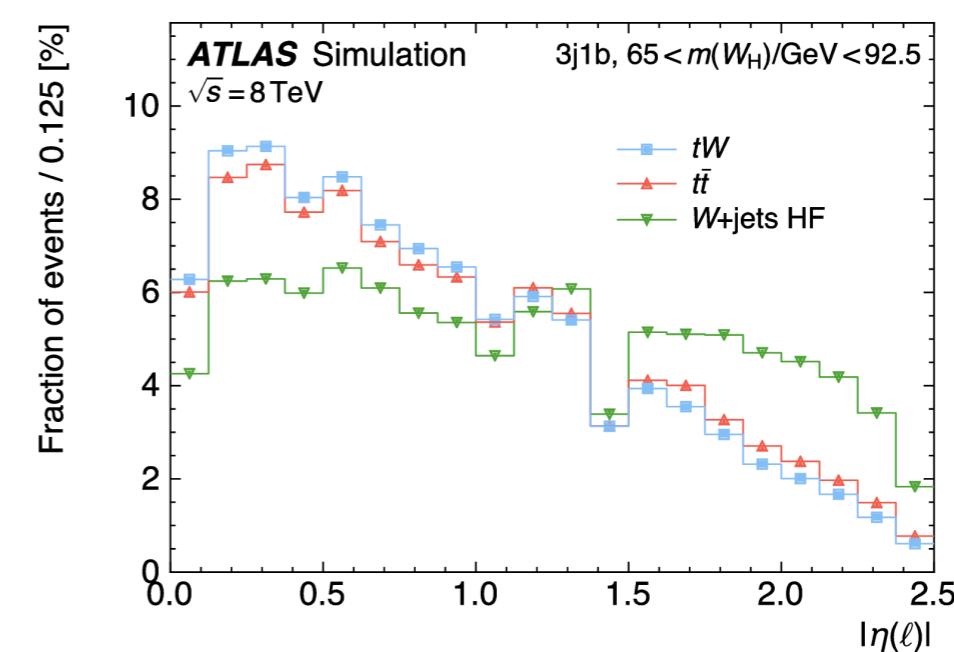
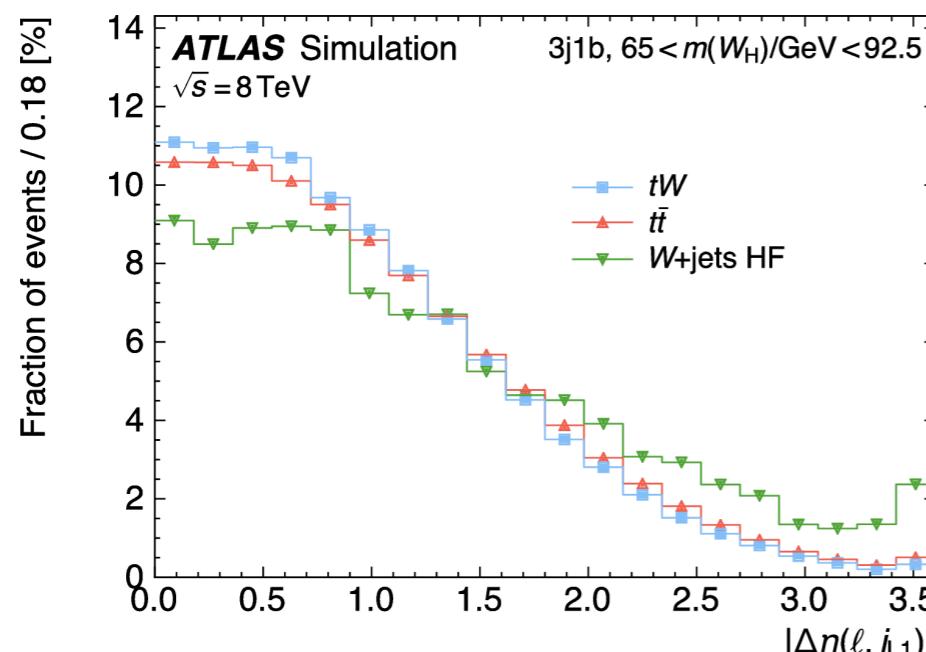
- The NN exploits the differences in the reconstruction of the tW system. Input variables:



$$\rho_T(W_H, W_L, j_B) = \frac{p_T(W_H W_L j_B)}{p_T(W_H) + p_T(W_L) + p_T(j_B)}$$

invariant mass of the reconstructed tW system

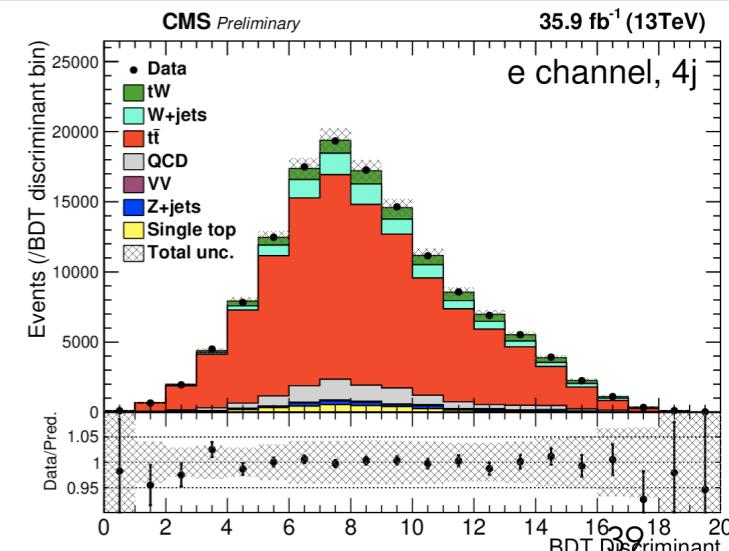
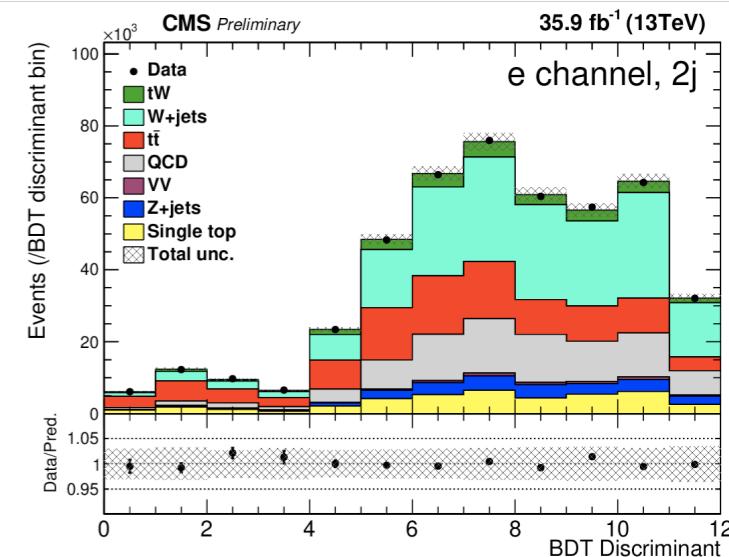
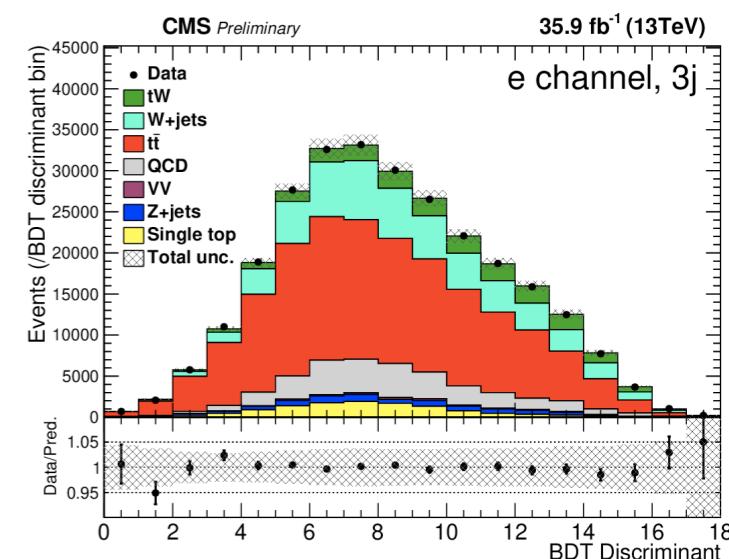
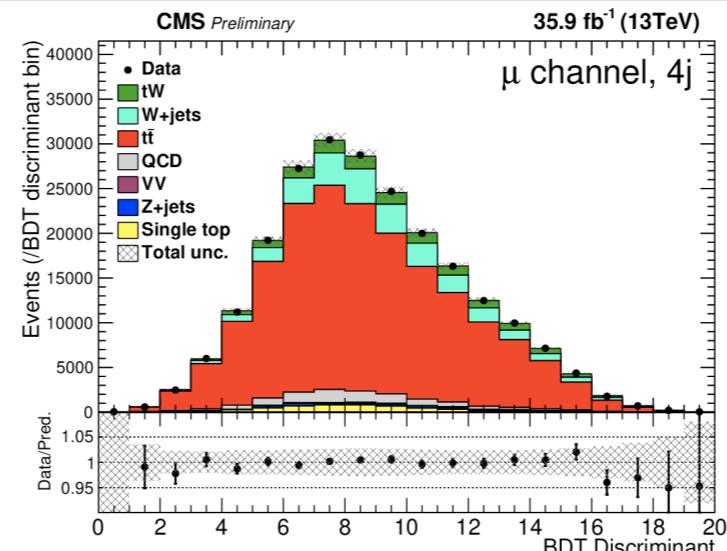
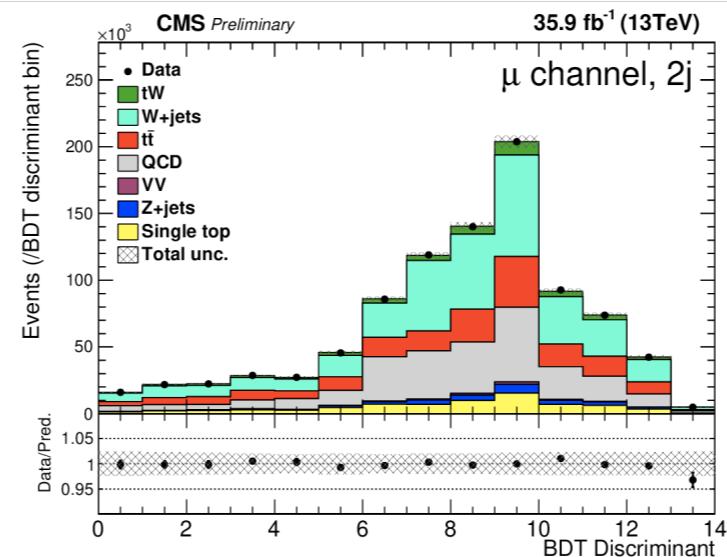
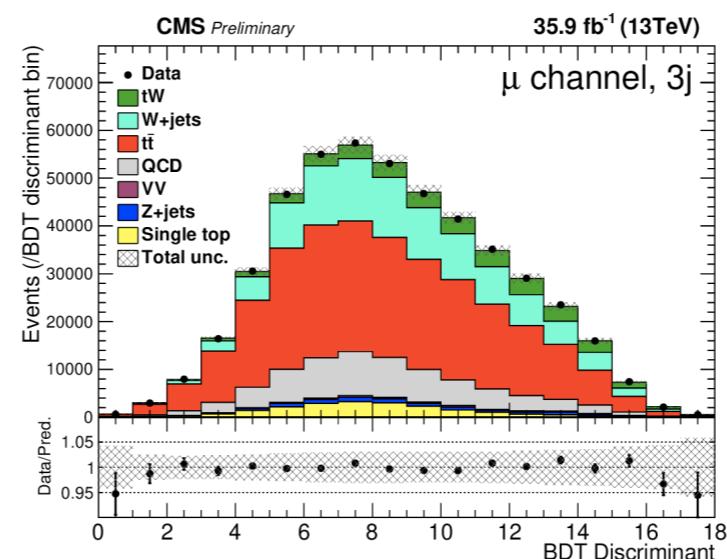
$p_T(W_H W_L j_B)$ transverse momentum of the tW system



CMS tW CROSS-SECTION MEASUREMENT

- A profile likelihood fit on the shape of the BDT discriminants is performed in the signal and control regions.
- The signal and control regions are splitted by lepton flavour.
- Nice agreement between the data and the SM expectations.

Sample	Muon channel		
	3j	2j	4j
tW	26091 ± 62	29772 ± 66	10580 ± 40
t <bar>t</bar>	272590 ± 360	196690 ± 300	184500 ± 300
W+jets	79800 ± 1200	332300 ± 3300	12000 ± 330
QCD multijet	67470 ± 320	275130 ± 700	10440 ± 140
Single top	15786 ± 55	54930 ± 100	4105 ± 28
Z+jets	7410 ± 500	26450 ± 970	2070 ± 240
VV	2850 ± 160	7450 ± 250	731 ± 81
Total prediction	472000 ± 2700	922700 ± 5700	224400 ± 1200
Data	472540	923880	223720



Sample	Electron channel		
	3j	2j	4j
tW	15725 ± 35	17453 ± 37	6578 ± 23
t <bar>t</bar>	157780 ± 200	111030 ± 160	109259 ± 160
W+jets	63400 ± 850	191000 ± 1800	9610 ± 250
QCD multijet	15370 ± 180	85080 ± 410	5960 ± 100
Single top	8939 ± 30	30223 ± 54	2375 ± 15
Z+jets	7080 ± 300	23830 ± 590	1800 ± 140
VV	1645 ± 85	4010 ± 130	461 ± 44
Total prediction	269900 ± 1700	462600 ± 3200	136000 ± 740
Data	270330	462930	136190

ATLAS $t\bar{Z}q$ OBSERVATION

- Signal and control regions definitions:

Common selections			
Exactly 3 leptons (e or μ) with $ \eta < 2.5$			
$p_T(\ell_1) > 28 \text{ GeV}$, $p_T(\ell_2) > 20 \text{ GeV}$, $p_T(\ell_3) > 20 \text{ GeV}$			
	$p_T(\text{jet}) > 35 \text{ GeV}$		
SR 2j1b	CR diboson 2j0b	CR $t\bar{t}$ 2j1b	CR $t\bar{t}Z$ 3j2b
≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSDF pair	≥ 1 OSSF pair
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	No OSSF pair	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$
2 jets, $ \eta < 4.5$	2 jets, $ \eta < 4.5$	2 jets, $ \eta < 4.5$	3 jets, $ \eta < 4.5$
1 b -jet, $ \eta < 2.5$	0 b -jets	1 b -jet, $ \eta < 2.5$	2 b -jets, $ \eta < 2.5$
SR 3j1b	CR diboson 3j0b	CR $t\bar{t}$ 3j1b	CR $t\bar{t}Z$ 4j2b
≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSDF pair	≥ 1 OSSF pair
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	No OSSF pair	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$
3 jets, $ \eta < 4.5$	3 jets, $ \eta < 4.5$	3 jets, $ \eta < 4.5$	4 jets, $ \eta < 4.5$
1 b -jet, $ \eta < 2.5$	0 b -jets	1 b -jet, $ \eta < 2.5$	2 b -jets, $ \eta < 2.5$

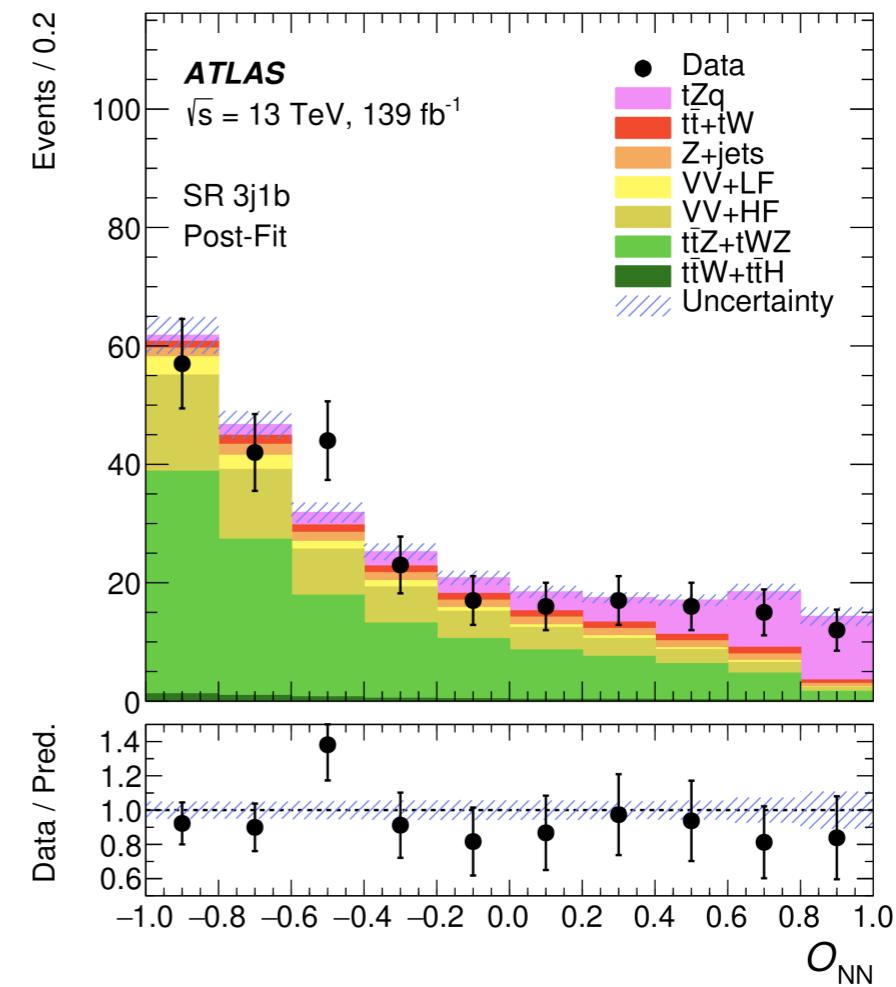
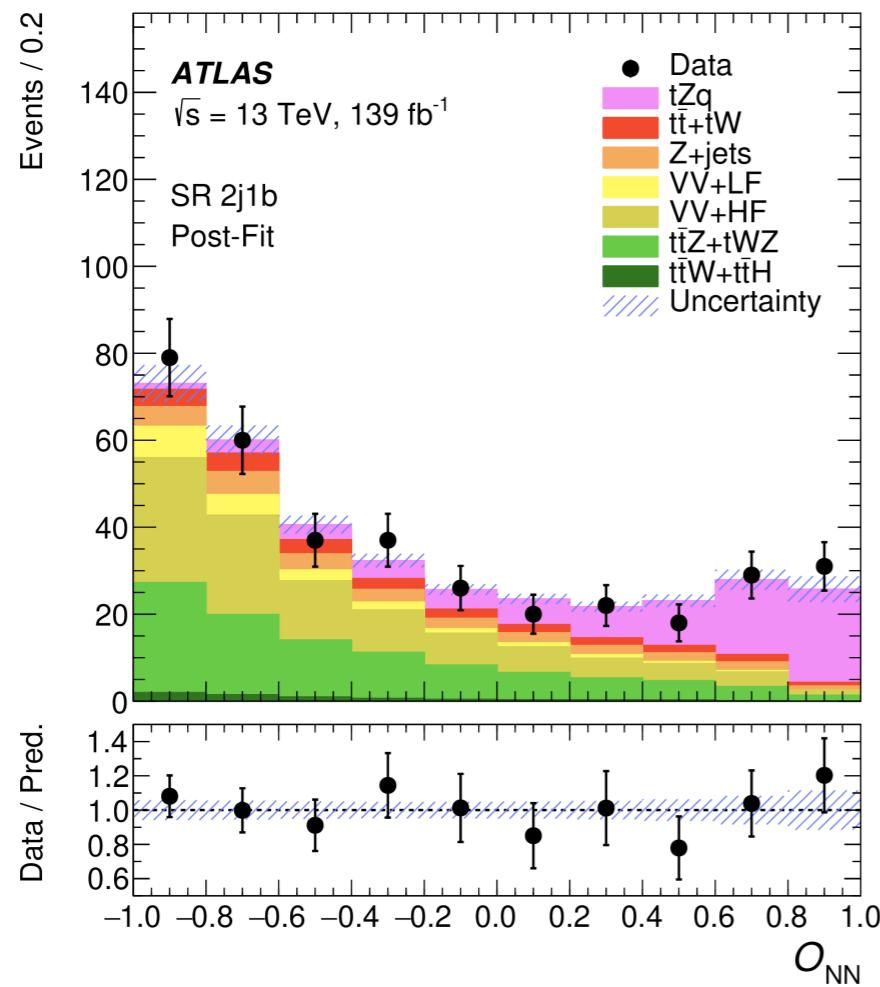
ATLAS $t\bar{Z}q$ OBSERVATION

- Yields in the signal and the control regions:

	SR 2j1b	CR diboson 2j0b	CR $t\bar{t}$ 2j1b	CR $t\bar{t}Z$ 3j2b
tZq	79 \pm 11	53.1 \pm 7.5	0.2 \pm 0.1	12.9 \pm 2.0
$t\bar{t} + tW$	23.8 \pm 4.8	13.7 \pm 2.7	33.3 \pm 6.3	1.7 \pm 0.3
$Z + \text{jets}$	28 \pm 13	181 \pm 82	< 0.1	1.4 \pm 0.6
$VV + \text{LF}$	19.7 \pm 7.9	2000 \pm 100	< 0.1	0.1 \pm 0.1
$VV + \text{HF}$	101 \pm 22	383 \pm 78	0.4 \pm 0.1	5.2 \pm 1.7
$t\bar{t}Z + tWZ$	96 \pm 11	63.2 \pm 7.0	4.8 \pm 0.5	59.3 \pm 7.1
$t\bar{t}H + t\bar{t}W$	6.5 \pm 1.0	3.0 \pm 0.5	12.4 \pm 1.9	2.8 \pm 0.5
Total	354 \pm 16	2697 \pm 56	51.1 \pm 6.1	83.5 \pm 6.4
Data	359	2703	49	92
	SR 3j1b	CR diboson 3j0b	CR $t\bar{t}$ 3j1b	CR $t\bar{t}Z$ 4j2b
tZq	43.4 \pm 6.2	21.2 \pm 3.3	0.2 \pm 0.1	8.0 \pm 1.3
$t\bar{t} + tW$	11.0 \pm 2.2	6.9 \pm 1.3	15.4 \pm 3.1	1.0 \pm 0.2
$Z + \text{jets}$	12.8 \pm 6.0	53 \pm 23	< 0.1	0.4 \pm 0.2
$VV + \text{LF}$	10.1 \pm 4.2	624 \pm 53	< 0.1	0.1 \pm 0.1
$VV + \text{HF}$	58 \pm 17	186 \pm 51	0.3 \pm 0.1	3.4 \pm 1.0
$t\bar{t}Z + tWZ$	132 \pm 12	61.9 \pm 6.2	3.9 \pm 0.5	58.1 \pm 5.3
$t\bar{t}H + t\bar{t}W$	4.7 \pm 0.7	1.7 \pm 0.3	8.2 \pm 1.3	2.0 \pm 0.3
Total	272 \pm 12	955 \pm 29	28.0 \pm 3.0	72.8 \pm 5.0
Data	259	949	31	75

ATLAS tZq OBSERVATION

- Background composition in the SRs:
 - 2j1b: 50% diboson; 32% $t\bar{t}Z + tWZ$.
 - 3j1b: $t\bar{t}Z$ (45%); Diboson (28%)
- NN used to further distinguish the signal from the backgrounds.
 - Exploits variables related with the Z boson reconstruction (reduces $t\bar{t}$).
 - Exploits top-quark related quantities (reduces backgrounds with no top quarks).
 - Exploits the large pseudorapidity of the final state untagged jet.



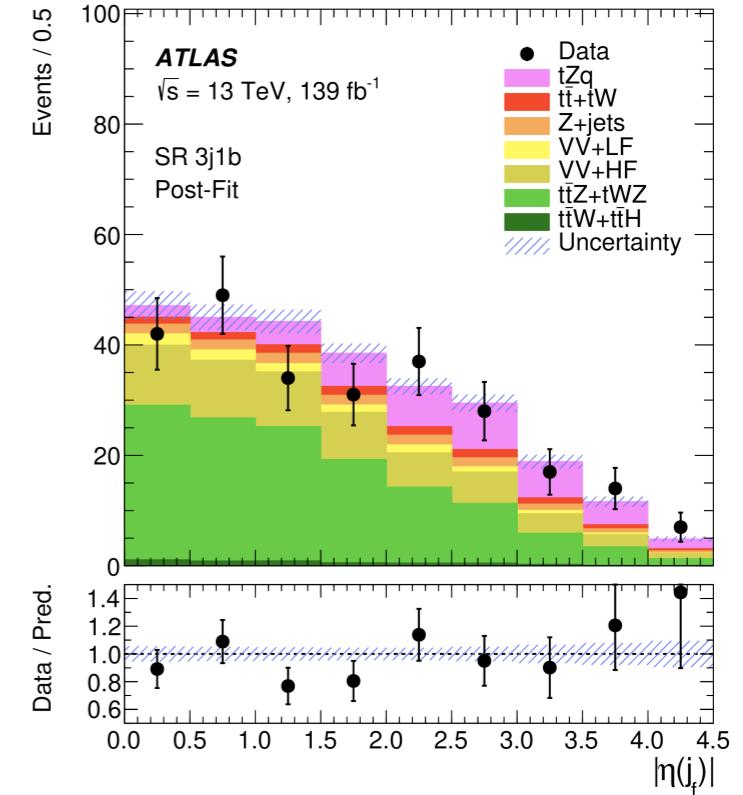
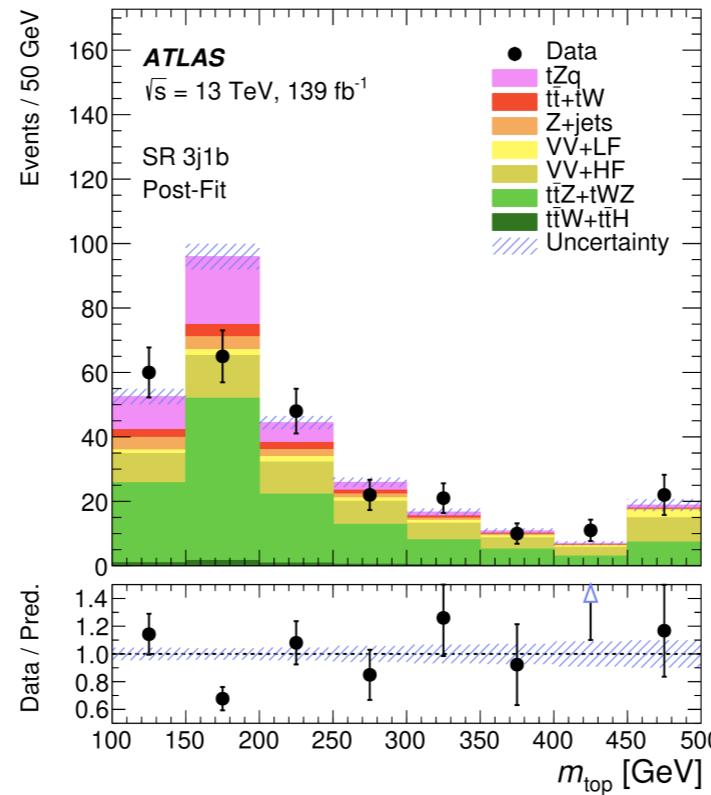
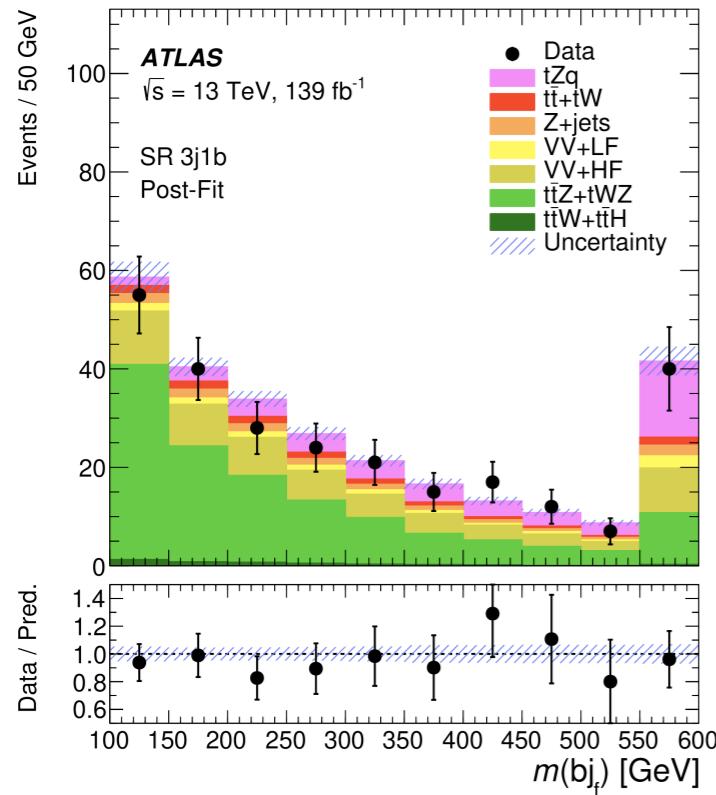
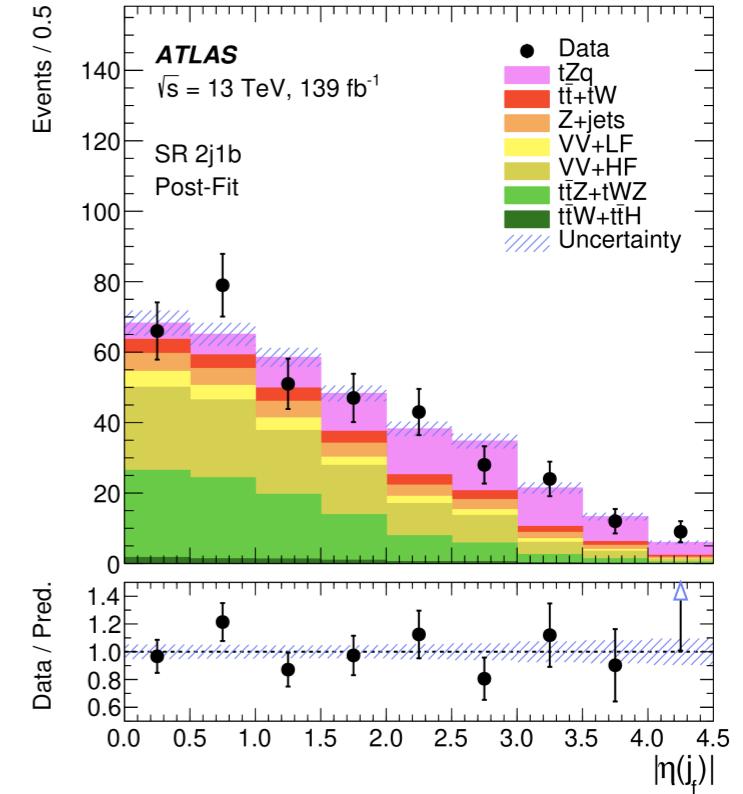
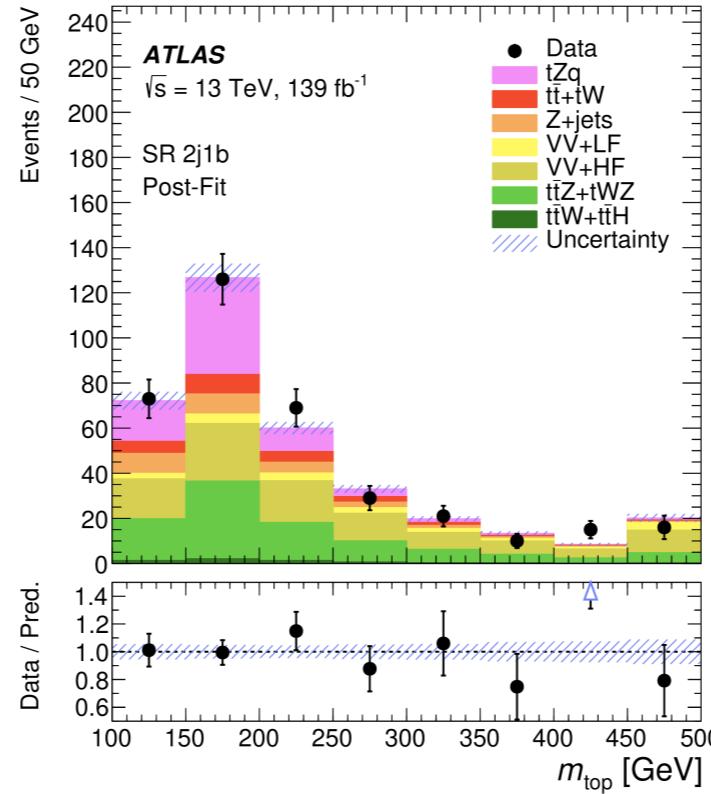
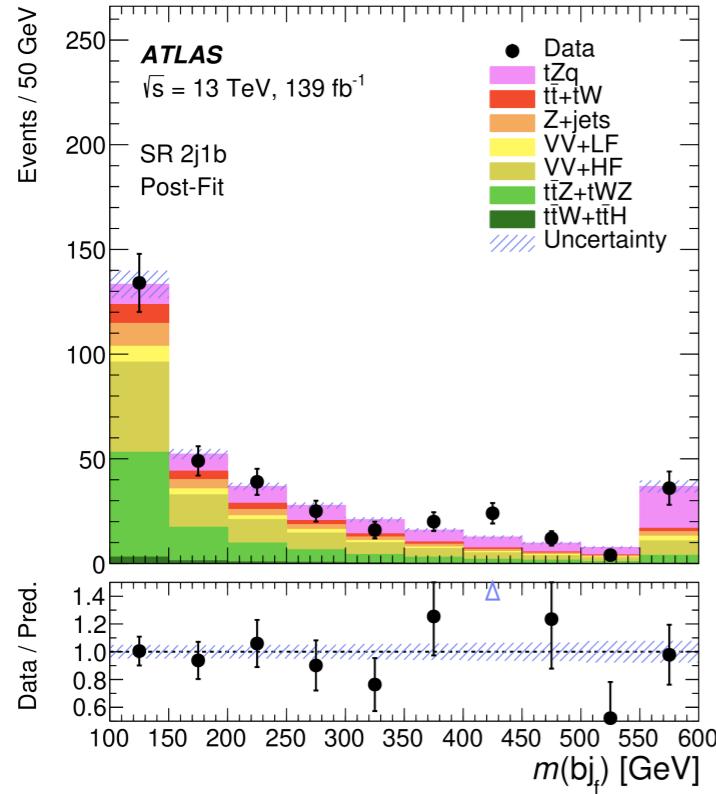
ATLAS tZq OBSERVATION

- NN is trained with 15 input variables.
- The training is different in the 2j1b and 3j1b signal regions.
- Same 4 variables are the highest ranked in the two signal regions.

Variable	Rank		Definition
	SR 2j1b	SR 3j1b	
m_{bj_f}	1	1	(Largest) invariant mass of the b -jet and the untagged jet(s)
m_{top}	2	2	Reconstructed top-quark mass
$ \eta(j_f) $	3	3	Absolute value of the η of the j_f jet
$m_T(\ell, E_T^{\text{miss}})$	4	4	Transverse mass of the W boson
b -tagging score	5	11	b -tagging score of the b -jet
H_T	6	–	Scalar sum of the p_T of the leptons and jets in the event
$q(\ell_W)$	7	8	Electric charge of the lepton from the W -boson decay
$ \eta(\ell_W) $	8	12	Absolute value of the η of the lepton from the W -boson decay
$p_T(W)$	9	15	p_T of the reconstructed W boson
$p_T(\ell_W)$	10	14	p_T of the lepton from the W -boson decay
$m(\ell\ell)$	11	–	Mass of the reconstructed Z boson
$ \eta(Z) $	12	13	Absolute value of the η of the reconstructed Z boson
$\Delta R(j_f, Z)$	13	7	ΔR between the j_f jet and the reconstructed Z boson
E_T^{miss}	14	–	Missing transverse momentum
$p_T(j_f)$	15	10	p_T of the j_f jet
$ \eta(j_r) $	–	5	Absolute value of the η of the j_r jet
$p_T(Z)$	–	6	p_T of the reconstructed Z boson
$p_T(j_r)$	–	9	p_T of the j_r jet

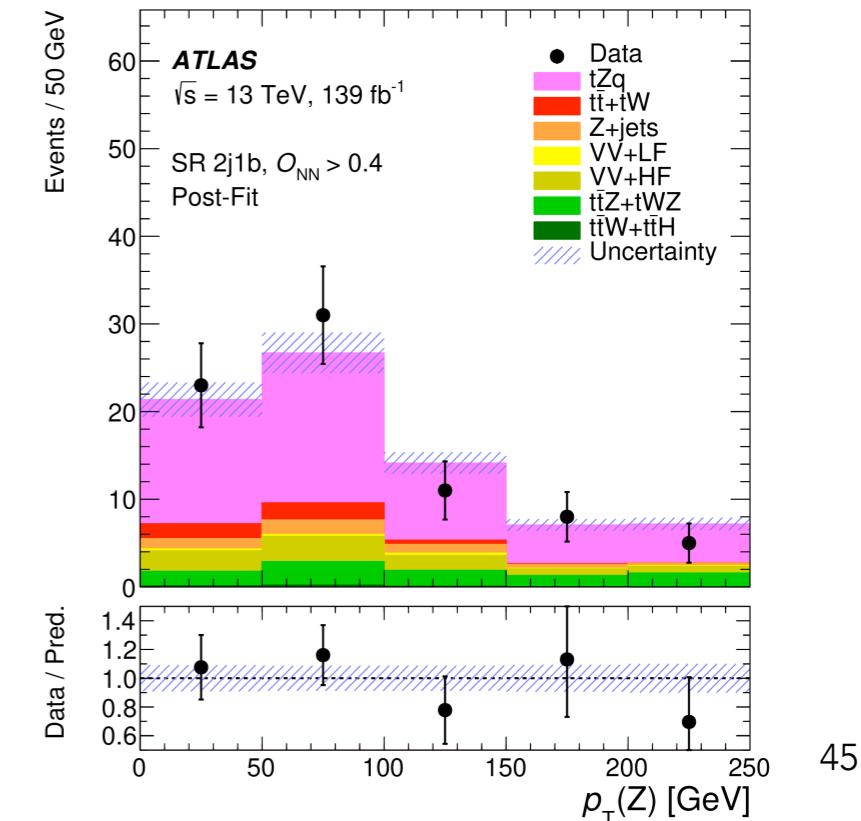
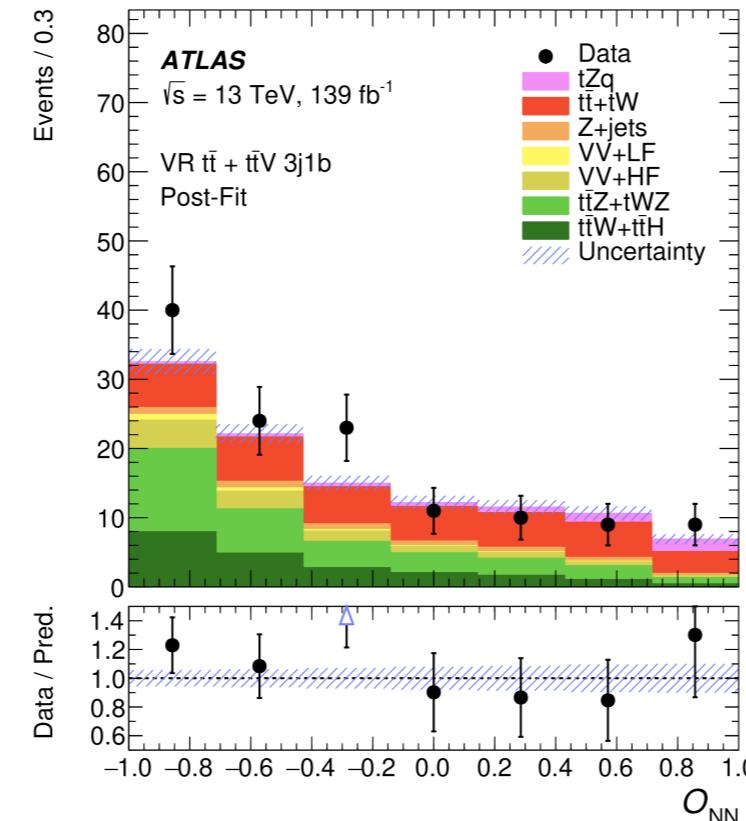
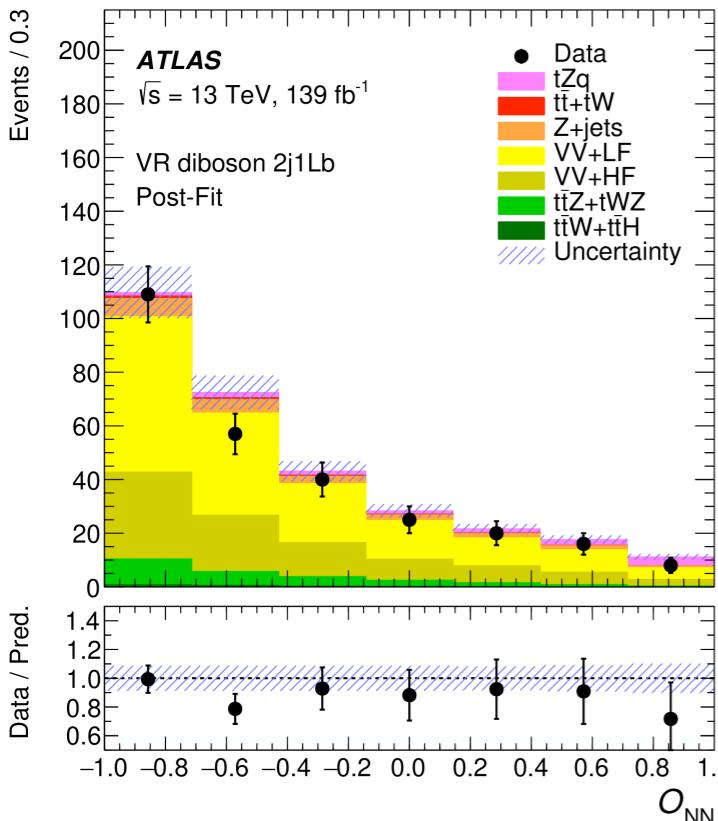
ATLAS tZq OBSERVATION

- Good modelling of the input variables:



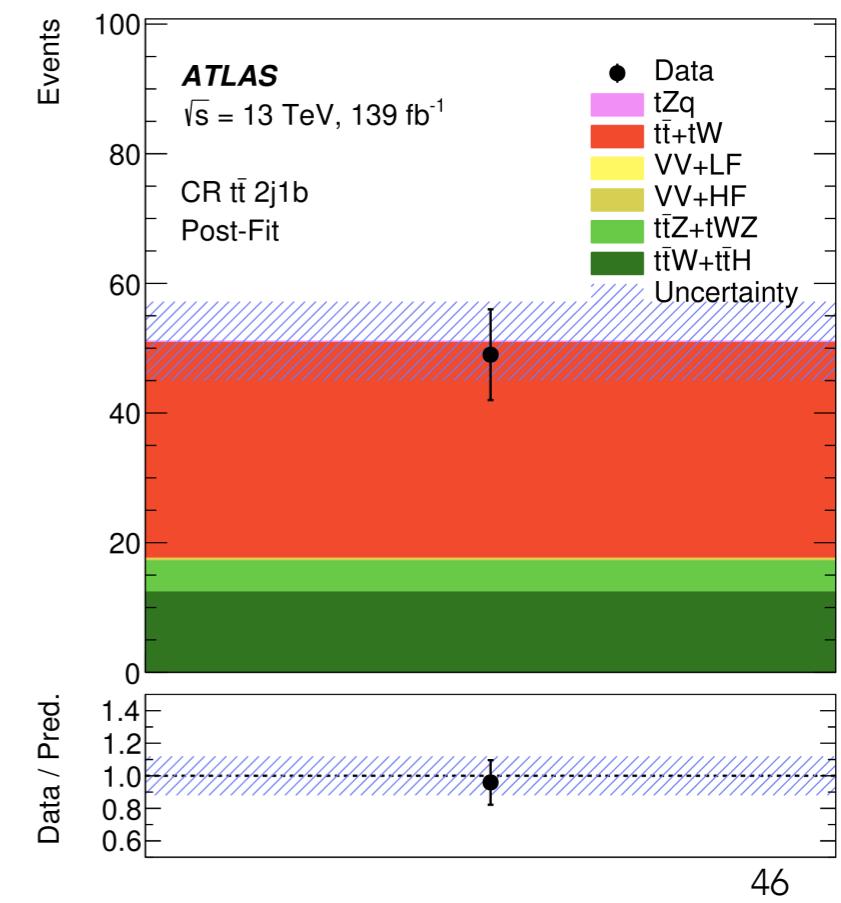
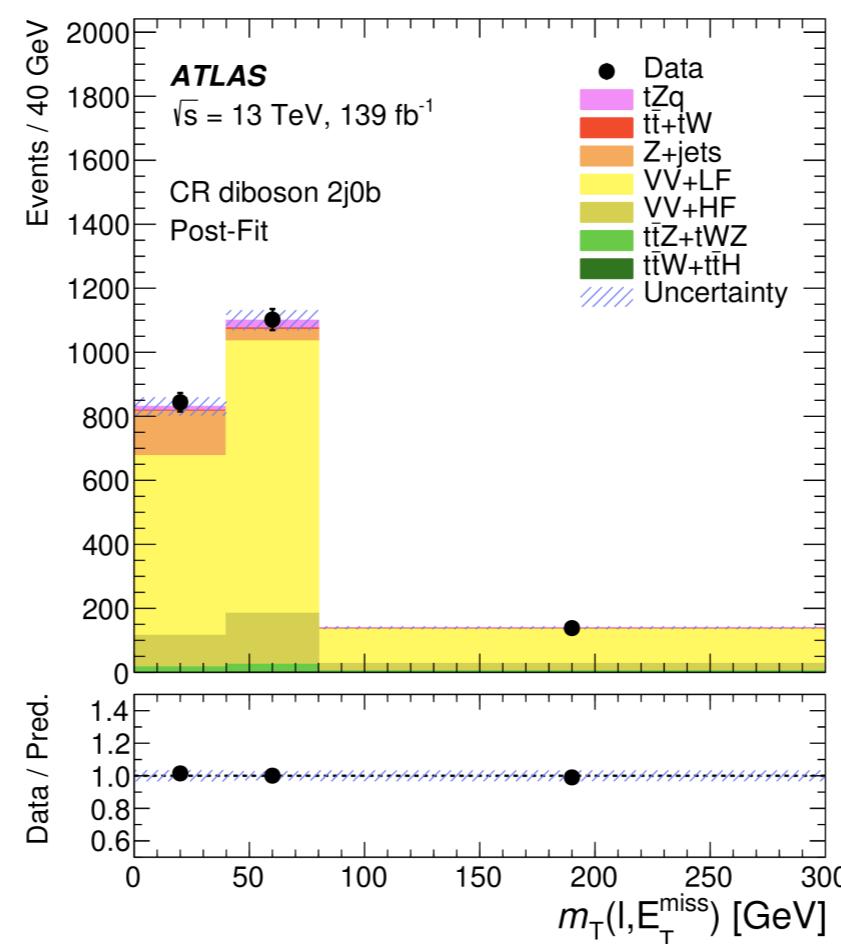
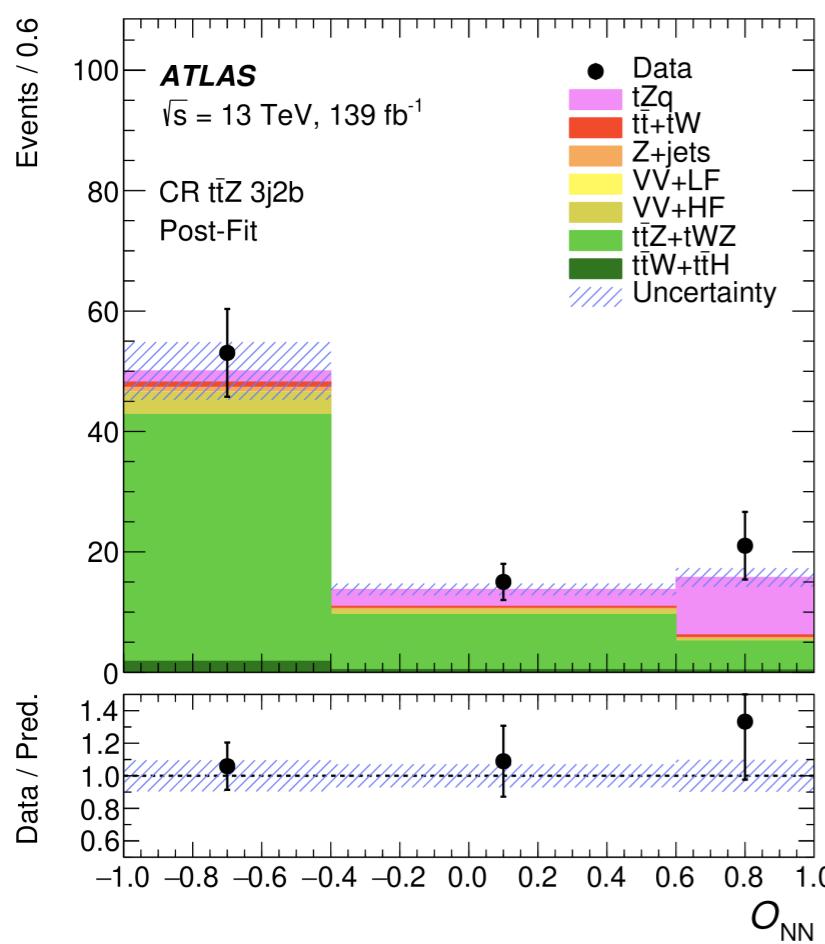
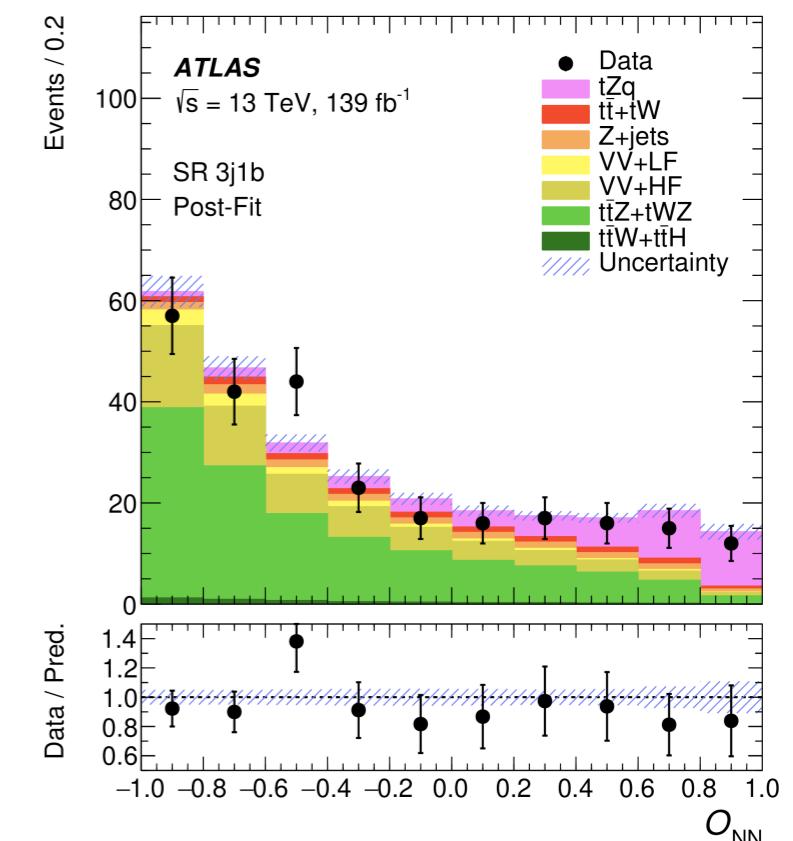
ATLAS tZq OBSERVATION

- Two different types of backgrounds:
 - 3 prompt leptons (diboson, $t\bar{t}Z$): Estimated using MC simulation.
 - 2 prompt leptons + 1 non-prompt lepton ($t\bar{t}$, $Z+jets$): Using b-jet replacement method.
- b-jet replacement method:
 - Assumes most of the non-prompt leptons come from a b-hadron.
 - The dilepton samples are extended to a trilepton sample forcing the semileptonic decay of a b-hadron.
 - Events are selected with one fewer lepton and one more b-jet than in the signal regions.
 - One of the b-jets is replaced by a lepton.
 - Normalisation extracted in specifically defined CRs.
- Validation regions used to check the modelling of the backgrounds (diboson, $t\bar{t} + t\bar{t}V$)
- Signal modelling is also validated in the SRs ($O_{NN} > 0.4$)



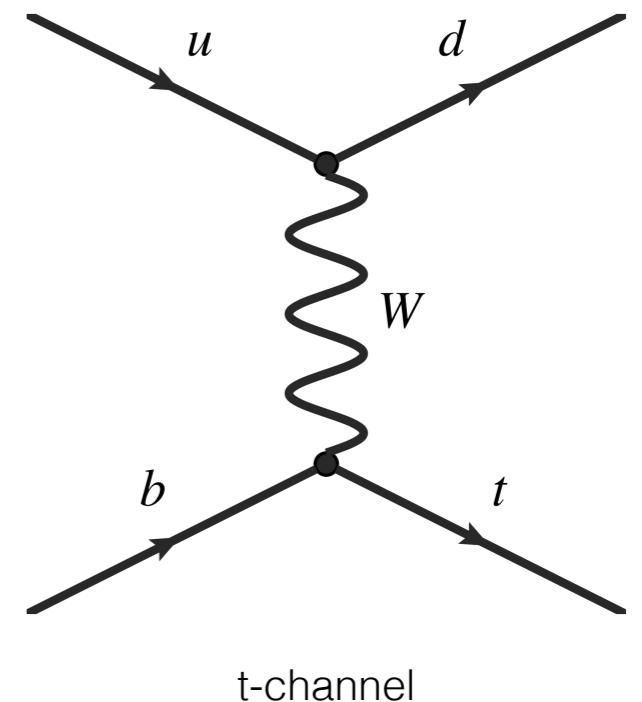
ATLAS tZq OBSERVATION

- Profile likelihood fit performed in the signal and control regions.
- The NN output is used in the SRs and the $t\bar{t}Z$ CRs.
- The reconstructed transverse mass of the W boson is used in the diboson CRs.
 - Discriminates between the Z+jets and the diboson backgrounds.
- Total events yields used in the $t\bar{t}$ CRs.



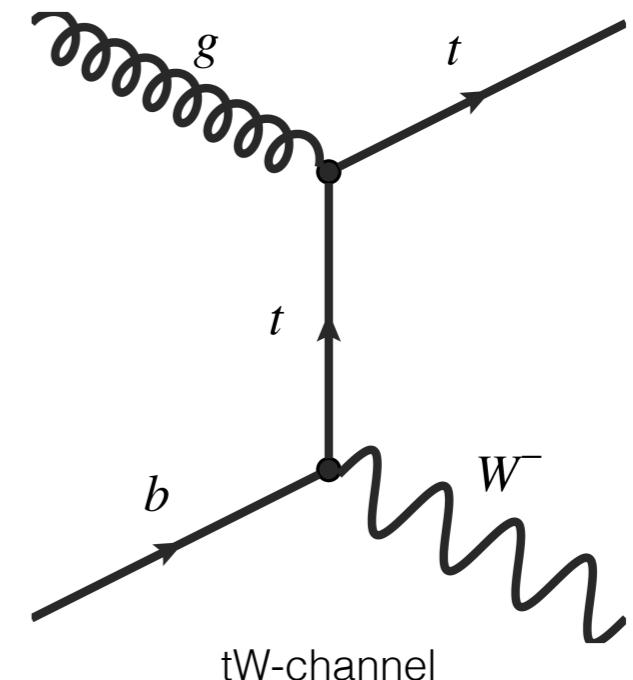
***t*-CHANNEL DIFFERENTIAL MEASUREMENTS: MOTIVATION**

- Useful to constrain:
 - EFT operators.
 - Top quark mass
 - Parton distribution functions
 - Renormalisation and factorisation scales.
- The ratio top-quark/antiquark is sensitive to the up to down quark content of the proton.
- Angular distributions are sensitive to the electroweak structure in the tWb vertex.

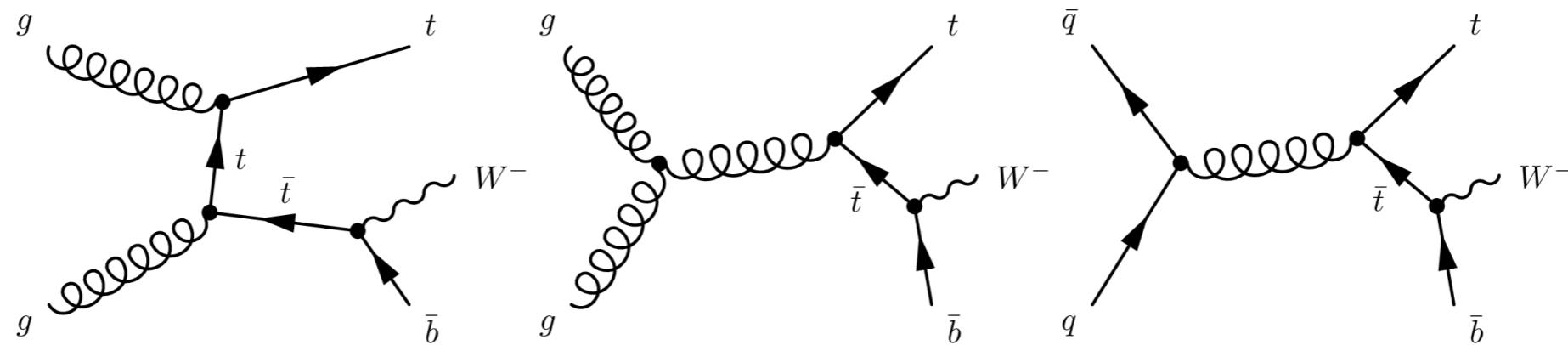


tW LEPTON+JETS FINAL STATE: MOTIVATION

- Most measurements to date are based on the dileptonic final state.
- The two measurements presented today focus on the semi-leptonic final state.
 - Larger branching ratio.
 - The presence of just one neutrino in the final state allows to fully reconstruct the kinematics of the W boson.
 - Larger background contamination.

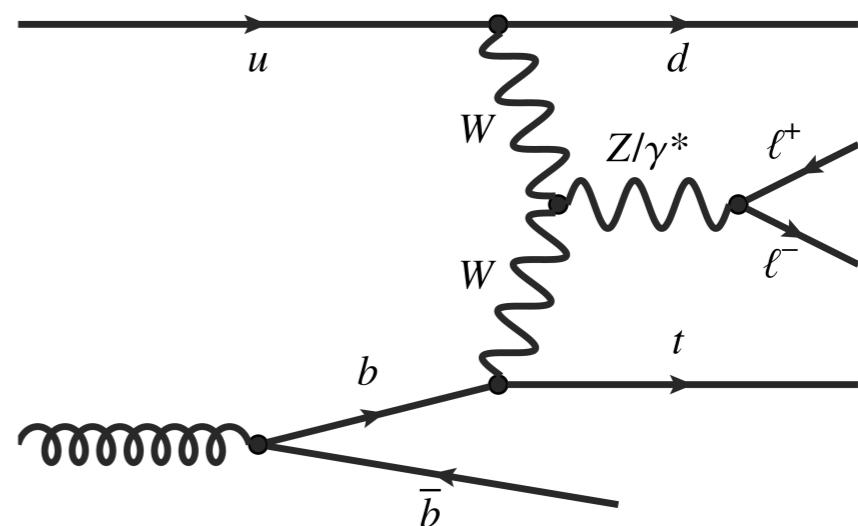
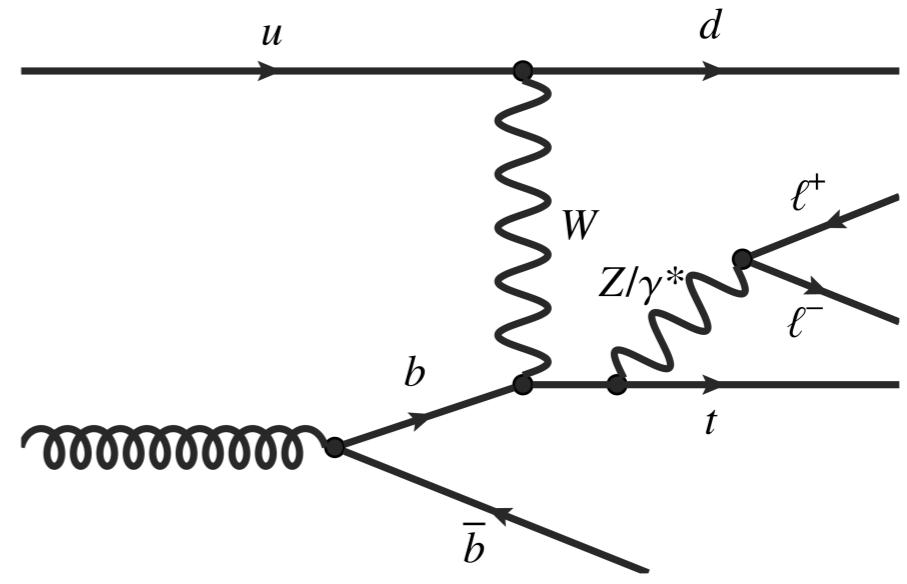


- Inclusive cross-section measurements provided by ATLAS and CMS at two different energies.
- tW is an important background in searches beyond the SM.
- Interference with $t\bar{t}$ @ NLO.

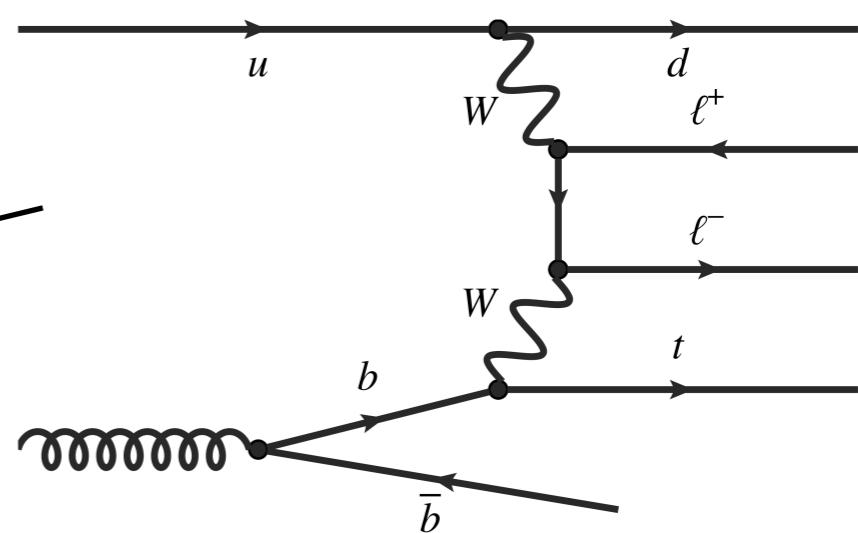


tZq : MOTIVATION

- Rare process. Previous results:
 - ATLAS @ 13 TeV (36 fb^{-1}): [arXiv:1710.03659](https://arxiv.org/abs/1710.03659)
 - Evidence 4.2σ
 - CMS @ 13 TeV (77.4 fb^{-1}): [Phys. Rev. Lett. 122, 132003 \(2019\)](https://doi.org/10.1103/PhysRevLett.122.132003)
 - First observation.
- Allows to study indirectly the tZ and WZ couplings.
- Small QCD corrections at NLO.
 - Deviations from SM predictions can be interpreted in an EFT context.



non-resonant production



PARTICLE LEVEL OBJECTS DEFINITION

- Particle-level objects are constructed from stable particles of the MC event record (ME+PS) with a lifetime $> 0.3 \cdot 10^{-10}$ s within the observable pseudorapidity range.
- These objects do not take into account any detector effect or any additional pp interactions (pile-up).
- More info: <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ParticleLevelTopDefinitions>

Object construction

The objects considered in the event record are stable particles (mean lifetime $> 0.3 \times 10^{-10}$ s) within the observable pseudorapidity range.

- **Photons:** photons used for final state definitions and for the definition of leptons (electron & muon) should not be from hadron decays. This removes the dependency on the underlying event.
- **Electron:** define 4-momentum from photons and electron within an anti- k_t R=0.1, where leptons (electron & muons) are considered for jet clustering. No isolation condition is imposed. In order to choose prompt leptons from W/Z decay in a way safe for all generators currently under consideration, the parent of the electron is required not to be a hadron or quark (u-b). (Expect that future sanitisation of generator record will remove the need for the quark requirement.)
- **Muon:** define 4-momentum from photons and muon within an anti- k_t R=0.1, where leptons (electron & muons) and photons are considered for jet clustering. No isolation condition is imposed. In order to choose prompt leptons from W/Z decay in a way safe for all generators currently under consideration, the parent of the muon is required not to be a hadron or quark (u-b). (Expect that future sanitisation of generator record will remove the need for the quark requirement.)
- **ETmiss/Neutrinos:** As an event level variable the missing transverse energy is calculated as the 4-vector sum of neutrinos from W/Z-boson decays. Tau decays are included. A neutrino is treated as a detectable particle and is selected for consideration in the same way as electrons or muons, i.e. the parent is required not to be a hadron or quark (u-b). (Expect that future sanitisation of generator record will remove the need for the quark requirement.)
- **Jets:** define with anti- k_t algorithm. Loop over all stable particles excluding the electrons, muons, neutrinos, and photons used in the definition of the selected leptons. This includes non-prompt muons and neutrinos for a proper b-jet energy scale. Use specific R parameter chosen by experiment: R=0.4 for ATLAS and R=0.5 for CMS.
- **b-jets:** A jet is a b-jet if any rescaled B-hadron is included in the jet. A rescaled B-hadron is treated as a stable B-hadron (that does not oscillate or decay to another B-hadron) for which the 4-momentum is scaled down by to the limit of floating point precision and added to the list of particles for jet-clustering as described above. Only B-hadrons with an initial $p_T > 5$ GeV are considered. This prescription provides an unambiguous way to associate a single jet with a B-hadron.
- **Further cuts in the event:** overlap removal, such as applied to reconstructed objects, does not make sense when the selected leptons are not included within jets. Instead, events where the leptons overlap with the selected jets should be discarded. For example, for a anti- k_t radius parameter of 0.4, events with $dR(\text{jet}, \text{el/mu}) < 0.4$ should be discarded.