Universidad de Oviedo
Universidá d'Uviéu
University of Oviedo

ICTEA
Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias

Single top (including V_{tb}, V_{ts}, V_{td}) at ATLAS and CMS

ALEJANDRO SOTO RODRÍGUEZ
(ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS)

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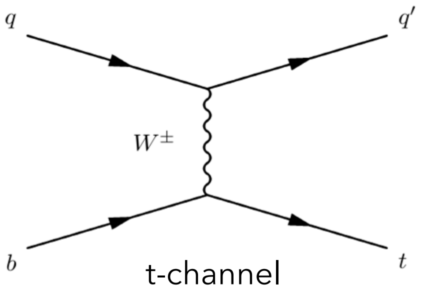
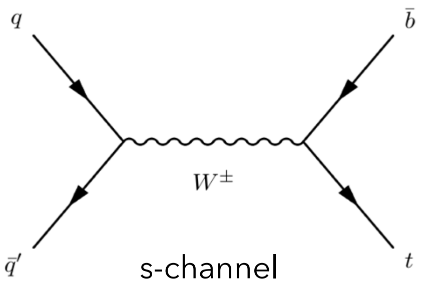
Introduction

- The top quark is the most massive particle in the SM.
  - Highest Yukawa coupling to the Higgs boson.
  - Due to its large mass, decays almost always before hadronizing.
- It has high interest in the LHC due to:
  - Multiple links with BSM physics.
  - Large presence of its production processes due to their large cross section.
- Top quark production occurs in two different ways: top pair (QCD) and **single top** (EW).
  - Allow to probe and measure V_{tb}, V_{ts} and V_{td}.
  - Top quark is polarised because of the tWb vertex.

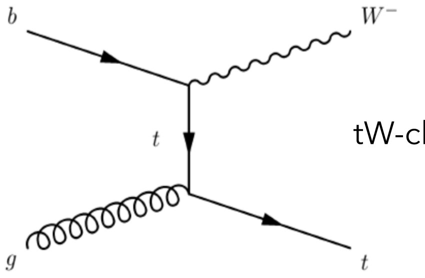
- M. Aliev et al., Comput.Phys.Commun.182:1034-1046,2011
- P. Kant et al., Comput.Phys.Commun. 191 (2015) 74-89
- N. Kidonakis, arXiv:1506.04072



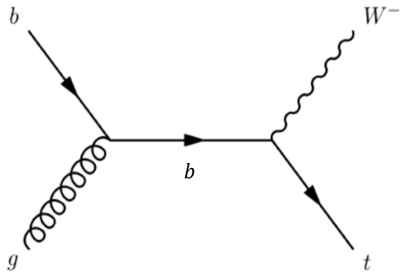
t-channel



s-channel



tW-channel



(13 TeV) $\sigma_{\text{t ch.}} = 217.0^{+6.6}_{-4.6}(\text{scale}) \pm 6.2(\text{PDF},\alpha_S)\,\text{pb}$

(13 TeV) $\sigma_{\text{s ch.}} = 10.32^{+0.29}_{-0.24}(\text{scale}) \pm 0.27(\text{PDF},\alpha_S)\,\text{pb}$

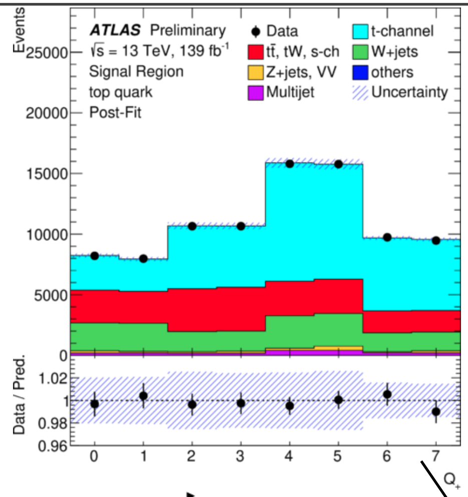
(13 TeV) $\sigma_{tW} = 71.7 \pm 1.8(\text{scale}) \pm 3.4(\text{PDF},\alpha_S)\,\text{pb}$

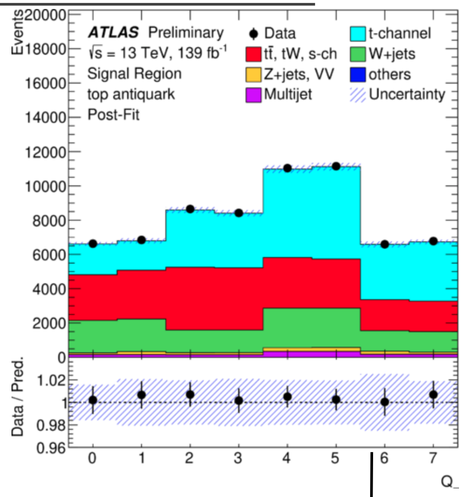
Polarisation measurement and bounds on the tWb dipole operator

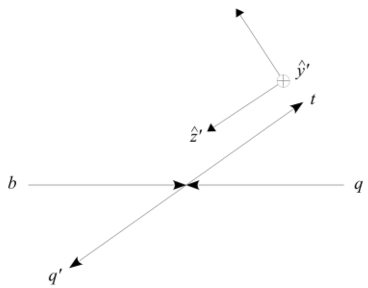
13 TeV, 139 fb^{-1}, t-channel

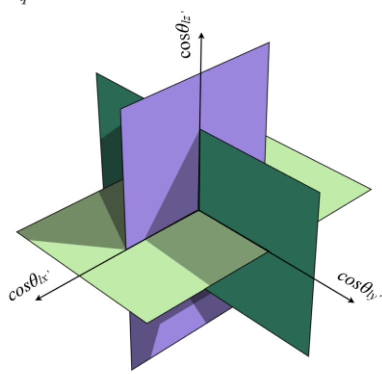
ATLAS-CONF-2021-027

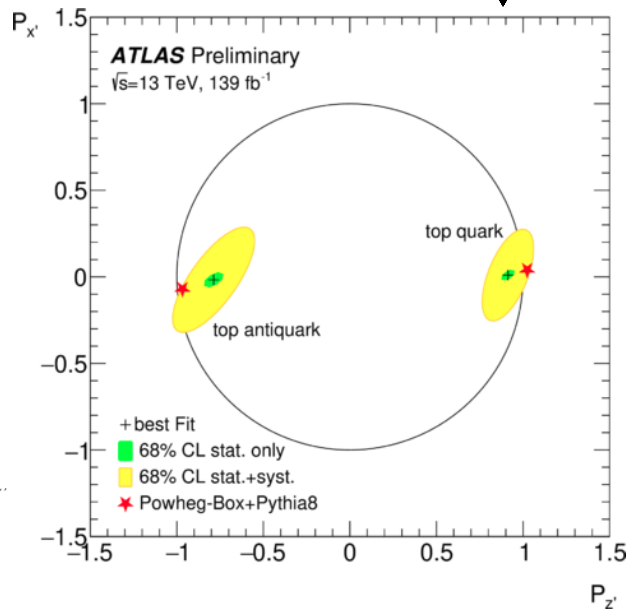
- **Event selection**:
  - One single central, isolated and energetic (>30 GeV) lepton, either muon or electron.
  - Looser leptons (in terms of p_{T} and other ID criteria) are vetoed to reduce contribution from backgrounds.
  - Exactly two energetic jets, of which one must be b-tagged.
  - Significant $p_{\mathrm{T}}^{\mathrm{miss}}$(> 35 GeV).
  - Cuts to avoid multijet background on the $m_{\mathrm{T}}(l, p_{\mathrm{T}}^{\mathrm{miss}})$ and $p_{\mathrm{T}}(l)$.
  - Further S/B enhancement on the pseudorapidity and invariant mass of the top quark and other systems, as well as the scalar sum of the p_{T} of all final-state objects.
- **First aim**: polarisation vector of single top/antitop quarks.
  - The direction of the charged lepton in the top quark rest frame is obtained, and with it, the values of $\cos\theta_{li'}$.
  - With it, a fit over 16 signal region bins depending on the value in the octant vector for both quark (Q_{+}) and antiquark (Q_{-}), and 4 control region bins (for $t\bar{t}$ and W+jets) is done.
  - **Protos** (LO generator) is used to obtain the projection of the joint PDF of the fully differential angular decay distribution onto the Q variable.
  - Result compatible with the prediction at NLO from Powheg+Pythia8.



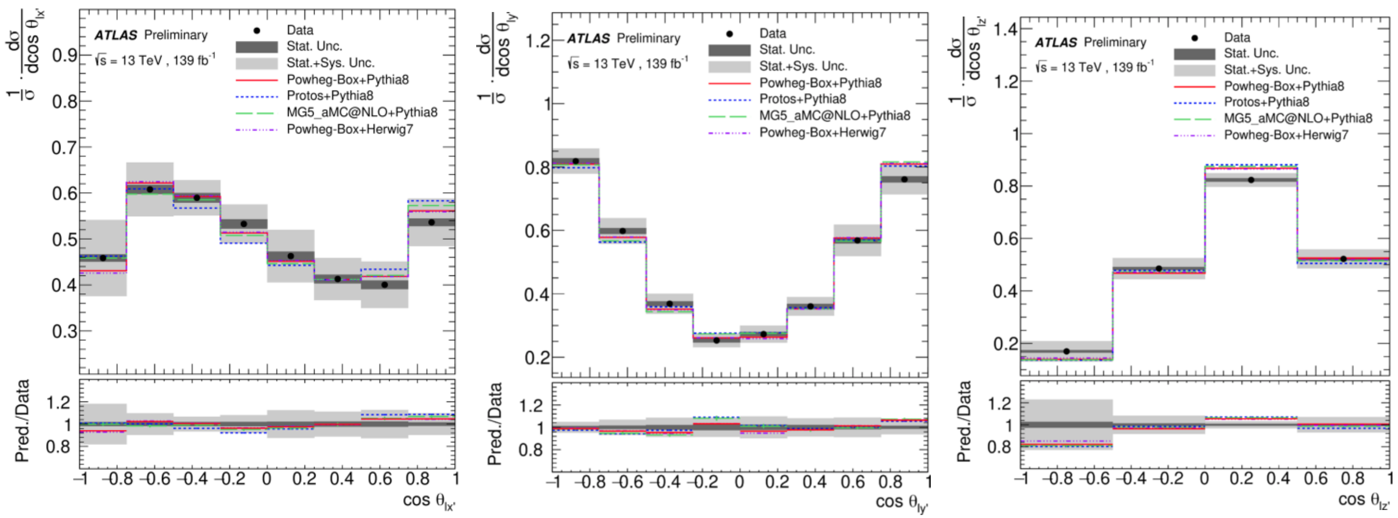


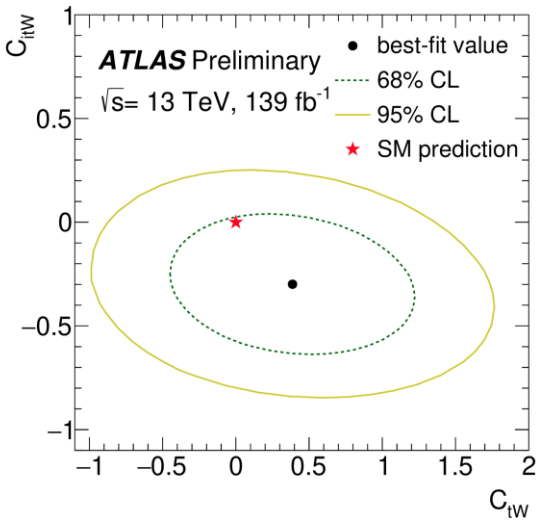




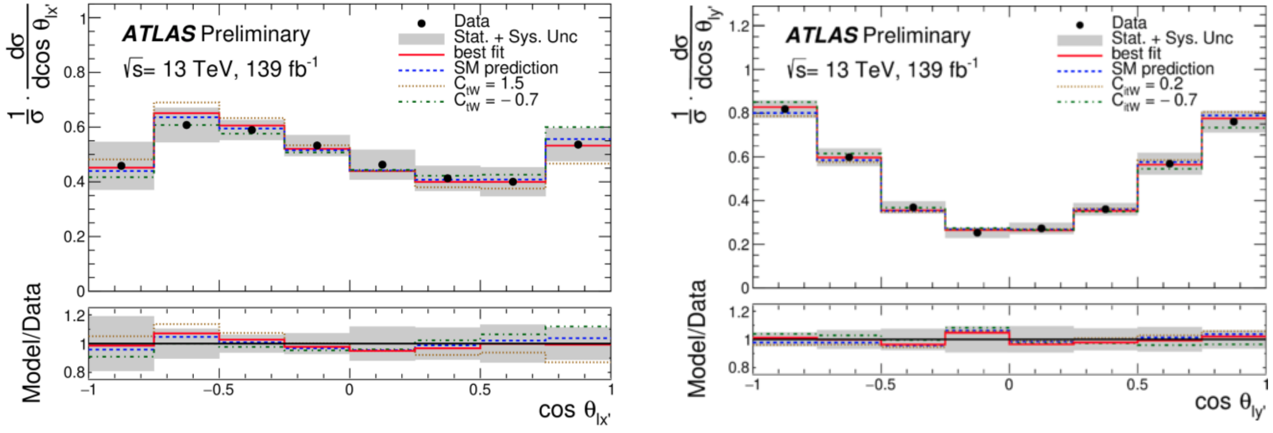


- **Second aim**: differential cross section of angular observables.
  - D'Agostini's iterative Bayesian method is implemented using RooUnfold.
  - Binning is optimised to get a stable unfolding. Bias introduced is checked to be negligible.
  - Result in agreement with predictions at NLO & LO QCD from generators interfaced with Pythia8 and Herwig7.





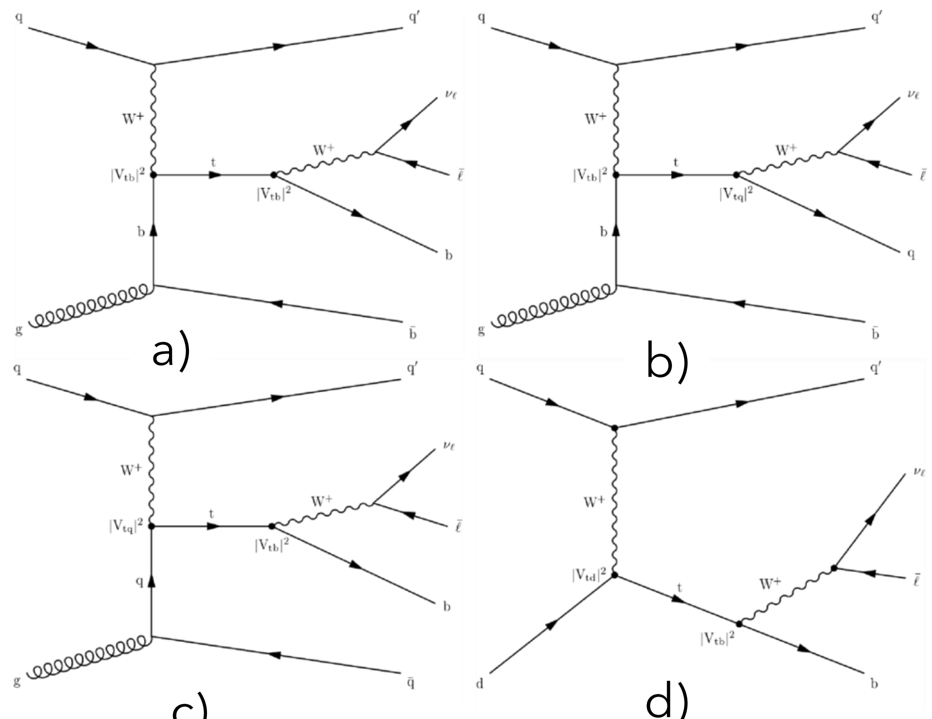
- **Third aim**: establish bounds on O_{tW} coefficients C_{tW} (real part) and C_{itW} (imaginary part).
  - An EFT expression depending on both coefficients is used to do a fit over the $\cos\theta_{ly'}$ and $\cos\theta_{lx'}$ distributions.
  - Results are in good agreement with the SM prediction.

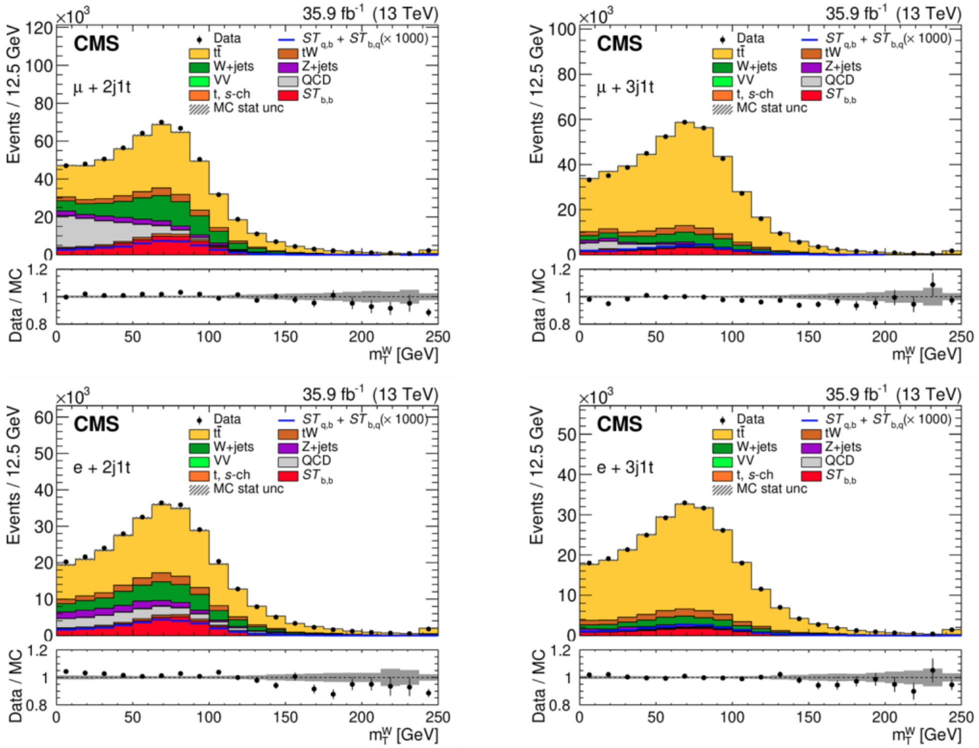


Measurement of CKM matrix elements

13 TeV, 35.9 $\mathbf{fb}^{-1}$, t-channel

Phys. Lett. B 808 (2020) 135609





- **Event selection**:
  - One single central, isolated and energetic (>30 GeV) lepton, either muon or electron.
  - At least two jets: either low-p_T ones (>20 GeV), or high- p_T jets (> 40 GeV).
  - $m_T(W)$ > 50 GeV.
  - Additional cut is imposed in the 3j2t region to enhance S/B ratio.

Category	Enriched in	Cross section × branching fraction	Feynman diagram
2j1t	$ST_{b,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wb)$	1a
3j1t	$ST_{b,q}$, $ST_{q,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wq)$, $\sigma_{t\text{-ch,q}}\mathcal{B}(t \to Wb)$	1b, 1c, 1d
3j2t	$ST_{b,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wb)$	1a

- **Strategy**: perform a maximum-likelihood fit on the 2j1t, 3j1t and 3j2t regions.
  - The signals are the t-ch. decay modes featuring different V_{tx} in their Feynman diagrams: $ST_{b,b'}$, $ST_{b,q}$ and $ST_{q,b'}$.
- MVAs (BDT) are trained for each region, and its discriminant is used in the ML fit.
  - Previously, two ML fit are done to extract the QCD/multijet background normalisations in the 2j1t and 3j1t regions.

Measurement of CKM matrix elements

13 TeV, 35.9 $\mathbf{fb}^{-1}$, t-channel

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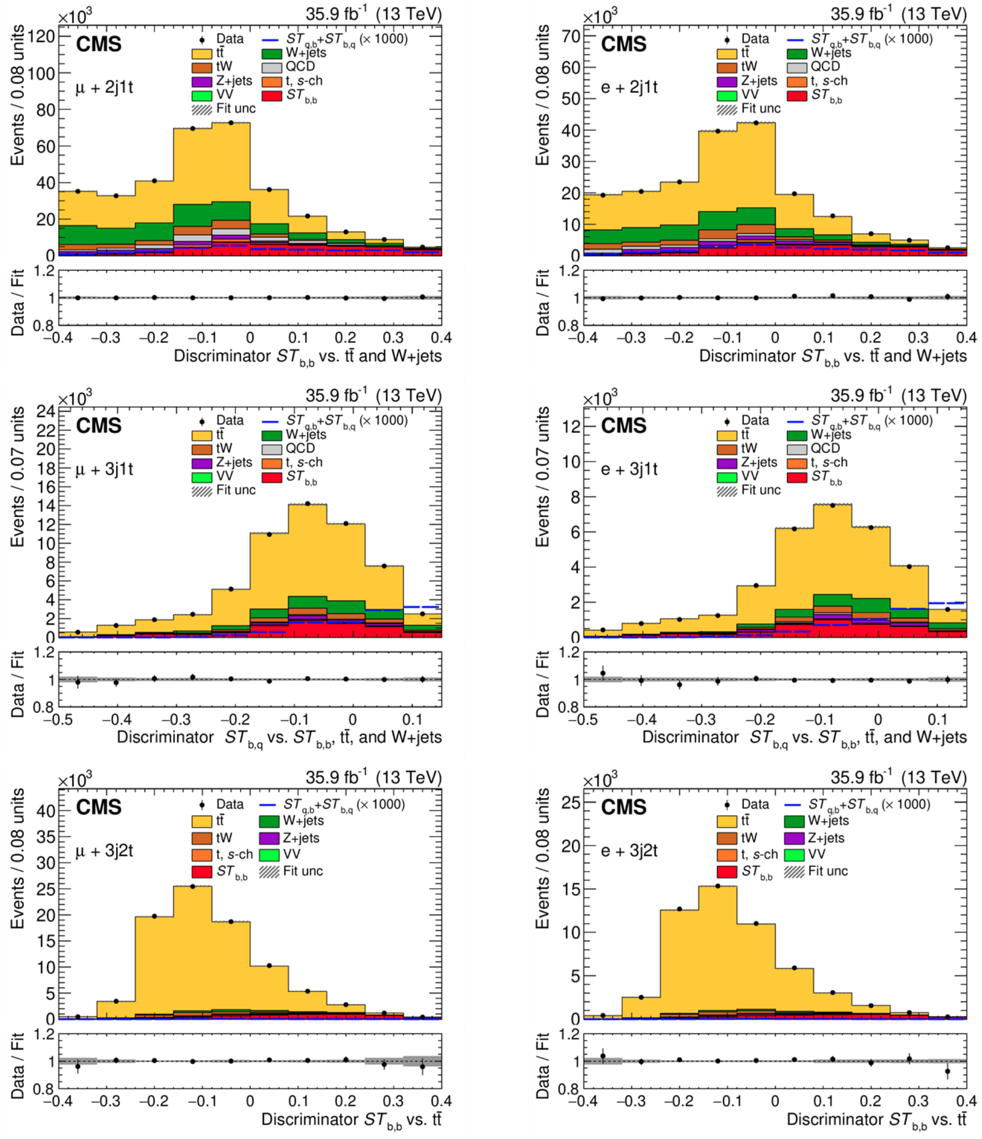


- The results for the signal strengths of the $ST_{b,b'}$ and the $ST_{b,q} + ST_{q,b'}$ are:

$$\mu_{\text{b}} = 0.99 \pm 0.03\,(\text{stat+prof}) \pm 0.12\,(\text{nonprof})$$

$$\mu_{\text{sd}} < 87 \text{ at } 95\% \text{ confidence level (CL)},$$

- Through approximations and neglecting small contributions, the results can be interpreted in different contexts:
  - **SM** case (imposing unitarity; 95% CL):

$$|V_{\text{tb}}| > 0.970$$
$$|V_{\text{td}}|^2 + |V_{\text{ts}}|^2 < 0.057.$$

  - **BSM case 1** (the top quark decays as in the SM, but the CKM matrix is modified):

$$|V_{\text{tb}}| = 0.988 \pm 0.027\,(\text{stat+prof}) \pm 0.043\,(\text{nonprof})$$
$$|V_{\text{td}}|^2 + |V_{\text{ts}}|^2 = 0.06 \pm 0.05\,(\text{stat+prof})\ ^{+0.04}_{-0.03}\,(\text{nonprof}).$$

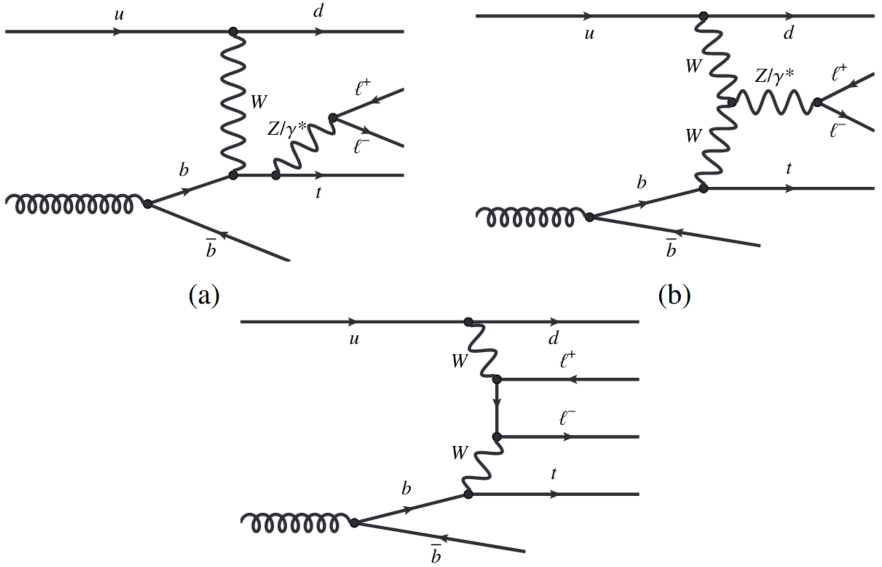
  - **BSM case 2** (the top quark decays in new unknown ways):

$$|V_{\text{tb}}| = 0.988 \pm 0.011\,(\text{stat+prof}) \pm 0.021\,(\text{nonprof})$$
$$|V_{\text{td}}|^2 + |V_{\text{ts}}|^2 = 0.06 \pm 0.05\,(\text{stat+prof}) \pm 0.04\,(\text{nonprof})$$
$$\frac{\Gamma_{\text{t}}^{\text{obs}}}{\Gamma_{\text{t}}} = 0.99 \pm 0.42\,(\text{stat+prof}) \pm 0.03\,(\text{nonprof}).$$

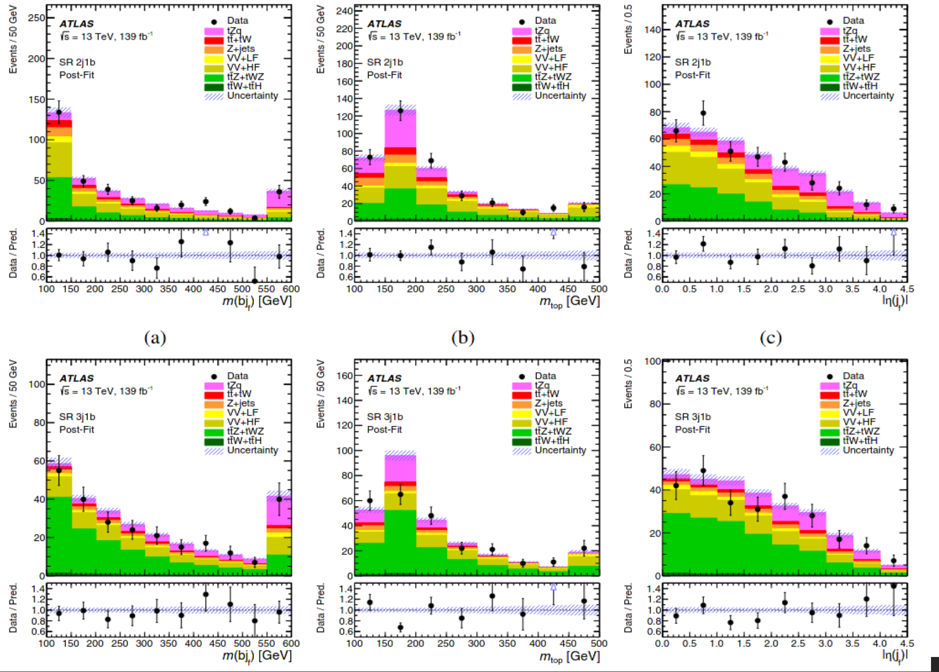
Inclusive measurement of tZq production

13 TeV, 139 $\mathbf{fb}^{-1}$, tZq process

JHEP 07 (2020) 124



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

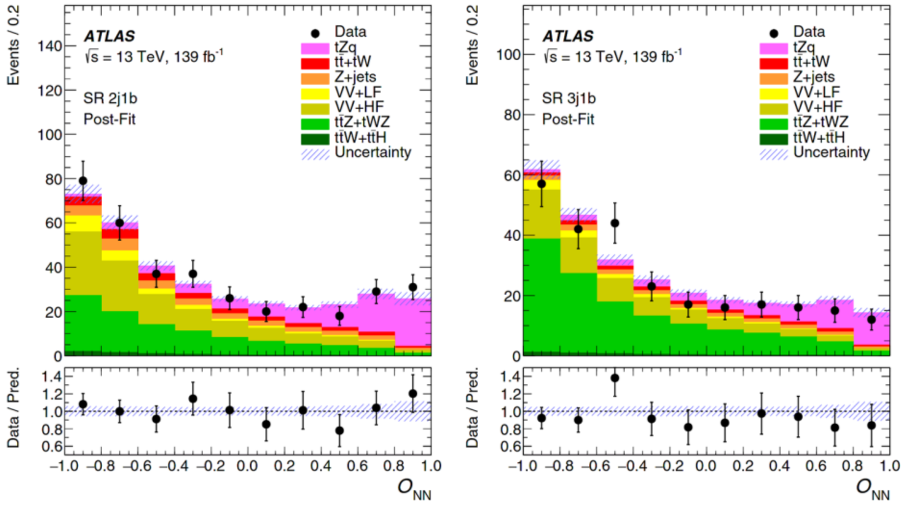


- **Strategy**:
  - Categorisation of events depending on the number of jets, and number of those b-tagged. Then, a ML fit is used to extract the signal.
  - For the signal regions (2j1b, 3j1b), two neural networks are trained, and their discriminant are used in the fit.
  - For the control regions various observables are used:
    - 2j0b, 3j0b → $m_T(l, p_T^{\text{miss}})$.
    - 2j1b, 3j1b → number of events (one bin).
    - 3j2b, 4j2b → the SR's NN discriminant are used.

Inclusive measurement of tZq production

13 TeV, 139 $\mathbf{fb}^{-1}$, tZq process

JHEP 07 (2020) 124



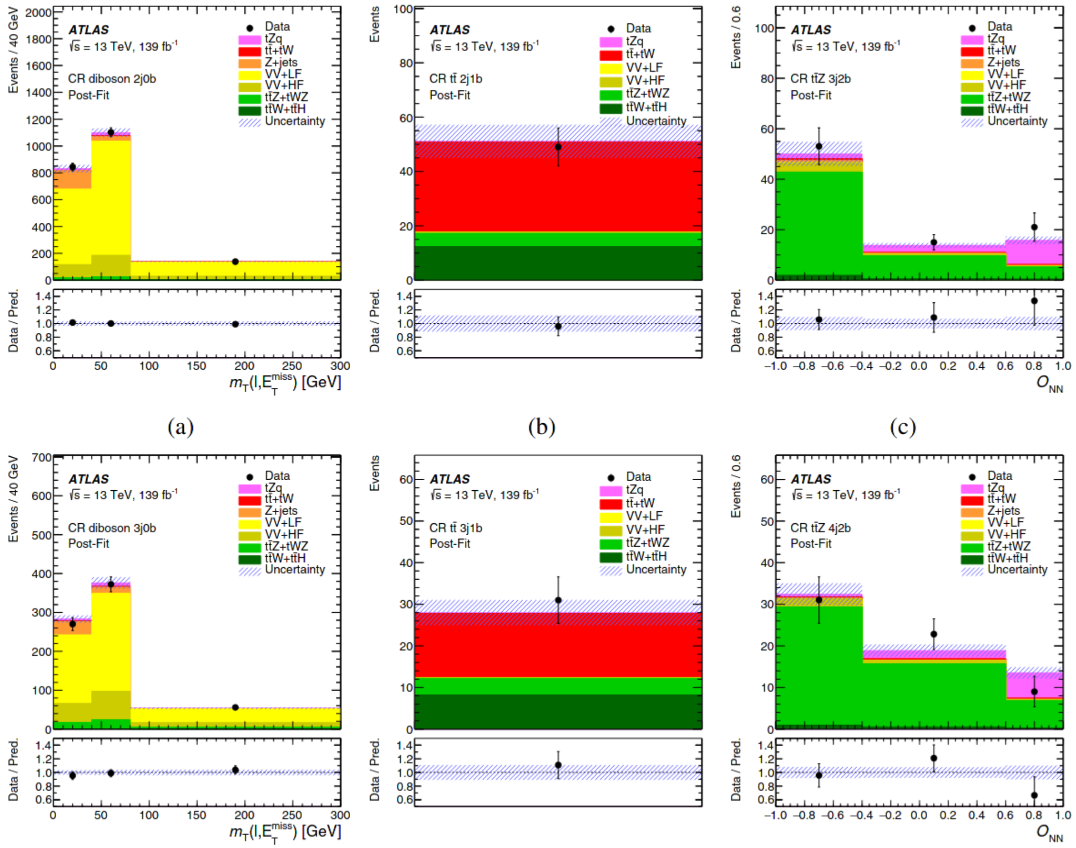
SR

$$\sigma_{\text{obs.}} = 97 \pm 13(\text{stat.}) \pm 7(\text{syst.})\text{fb}$$

$$\sigma_{\text{pred.}} = 102^{+5}_{-2}\ \text{fb}$$

JHEP 2014, 79 (2014)

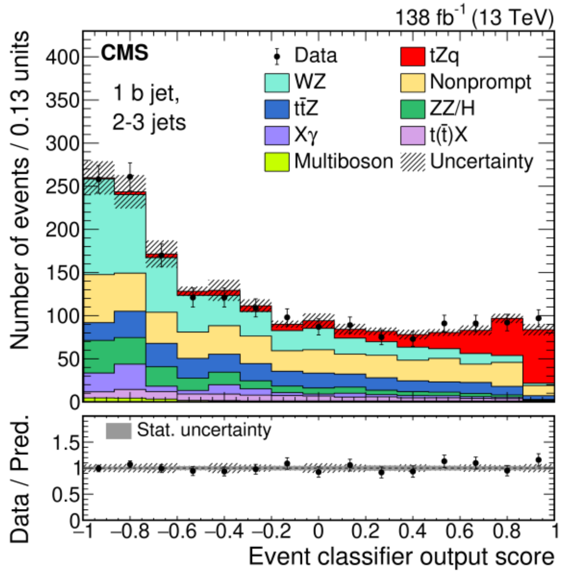
CR

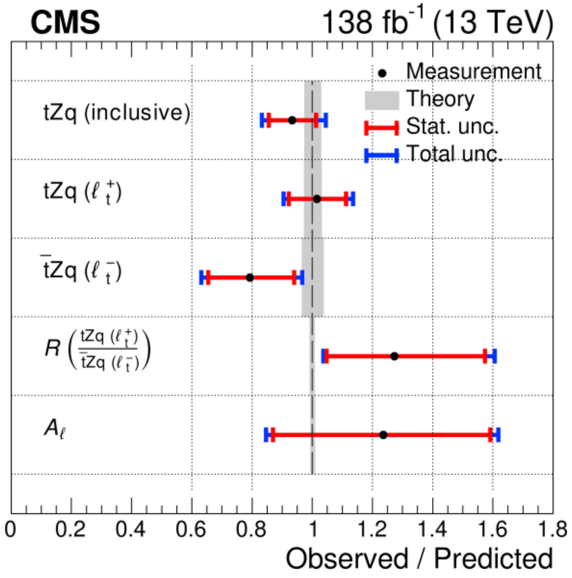


Uncertainty source	$\Delta\sigma/\sigma$ [%]
Prompt-lepton background modelling and normalisation	3.3
Jets and $E_{\text{T}}^{\text{miss}}$ reconstruction and calibration	2.0
Lepton reconstruction and calibration	2.0
Luminosity	1.7
Non-prompt-lepton background modelling	1.6
Pile-up modelling	1.2
MC statistics	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

- **Event selection**:
  - Three central and energetic leptons (p_T > 25, 15, 10 GeV), two of them should form an OSSF pair with invariant mass compatible with that of a Z boson.
  - At least two energetic jets (p_T > 25 GeV), of which at least one should be b tagged.
- Non-prompt backgrounds are estimated through data-driven methods.
- **Inclusive measurement strategy:**
  - An MVA output is used to do a maximum-likelihood fit and extract the signal.
  - Control regions are defined to constrain the WZ and Zγ backgrounds.
  - The inclusive, as well as the separated contributions per charge of the lepton coming from the top of the tZq process and its ratio are extracted.

$$\sigma_{\mathrm{tZq}(\ell_t^+)} = 62.2\ ^{+5.9}_{-5.7}\ \mathrm{(stat)}\ ^{+4.4}_{-3.7}\ \mathrm{(syst)\ fb}$$
$$\sigma_{\bar{\mathrm{t}}\mathrm{Zq}(\ell_t^-)} = 26.1\ ^{+4.8}_{-4.6}\ \mathrm{(stat)}\ ^{+3.0}_{-2.8}\ \mathrm{(syst)\ fb}$$
$$R = 2.37\ ^{+0.56}_{-0.42}\ \mathrm{(stat)}\ ^{+0.27}_{-0.13}\ \mathrm{(syst)}\ .$$





Inclusive and differential measurement of tZq production

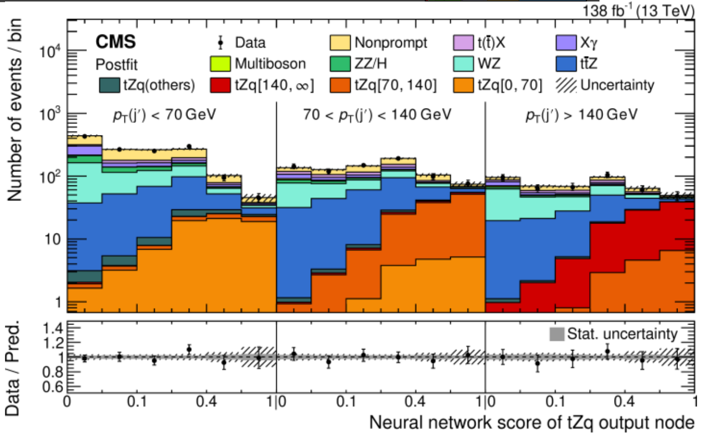
13 TeV, 138 $\mathbf{fb}^{-1}$, tZq

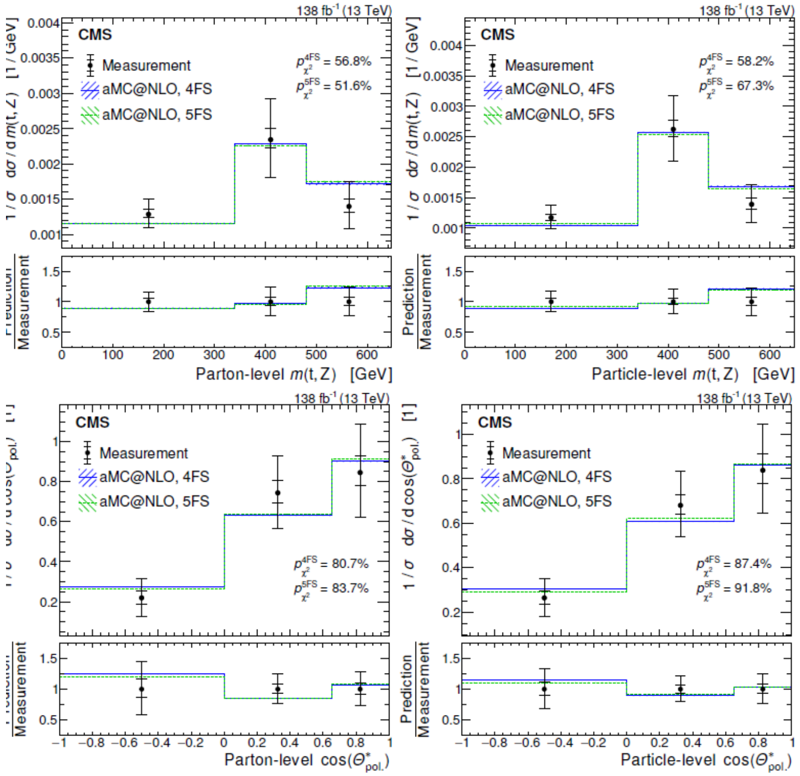
Sub. to JHEP, arXiv: 2111.02860

- **Differential measurement strategy**
  - An MVA output is used per bin of particle (or parton) level to do a maximum-likelihood fit and extract the signal and perform the unfolding in one step.
  - Control regions are defined as in the inclusive measurement to constrain background normalisations.
  - Results are later normalised to the fiducial cross section.
  - From the differential distribution of the top quark polarisation angle, the top quark spin asymmetry is also measured.
  - Results are in overall agreement with SM expectations.

$$\cos(\theta^{\star}_{\text{pol}}) = \frac{\vec{p}(q'^{\star}) \cdot \vec{p}(\ell^{\star}_{t})}{|\vec{p}(q'^{\star})||\vec{p}(\ell^{\star}_{t})|} \qquad \frac{d\sigma}{d\cos(\theta^{\star}_{\text{pol}})} = \sigma_{tZq}\left(\frac{1}{2} + A_{\ell}\cos(\theta^{\star}_{\text{pol}})\right)$$

$$A_{\ell} = 0.54 \pm 0.16\,(\text{stat}) \pm 0.06\,(\text{syst})$$



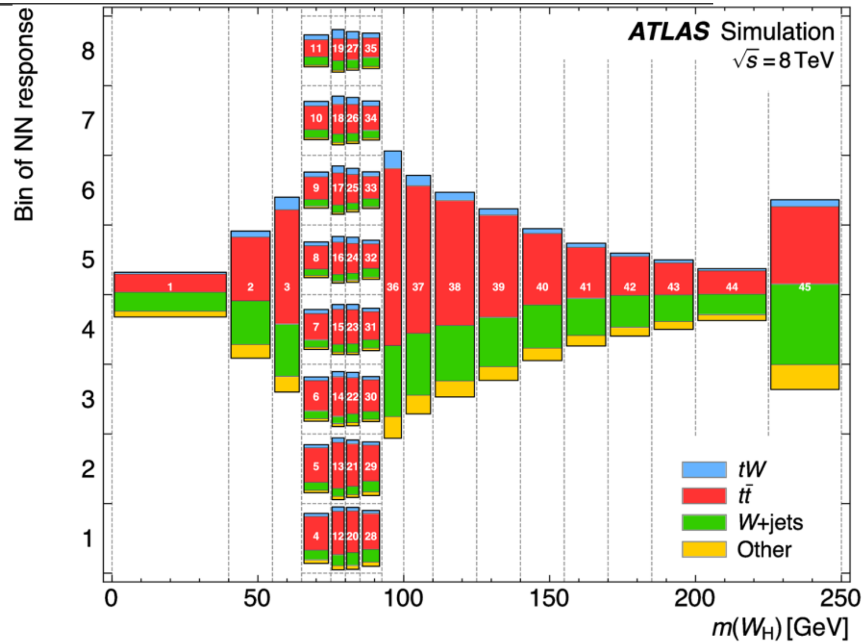


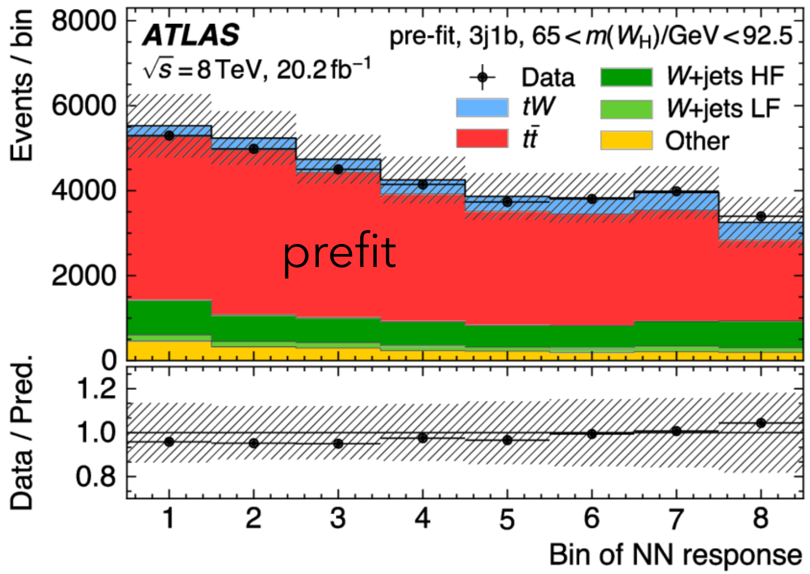
Measurement of tW production (semileptonic channel)

8 TeV, 20.2 $\mathbf{fb}^{-1}$, tW channel

Eur. Phys. J. C 81 (2021) 720

- **Event selection**:
  - One energetic (> 30 GeV), isolated and central electron or muon.
  - Veto of less energetic leptons (> 25 GeV).
  - $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV.
  - $m_{\mathrm{T}}(W_{\mathrm{L}}) > 50$ GeV.
- **Strategy**:
  - Signal region: 3j1b.
  - A 2-dimensional discriminant is constructed with a neural network output in 65 GeV < $m(W_{\mathrm{H}})$ < 92.5 GeV and with the remaining $m(W_{\mathrm{H}})$ variable.





Eur. Phys. J. C 81 (2021) 720

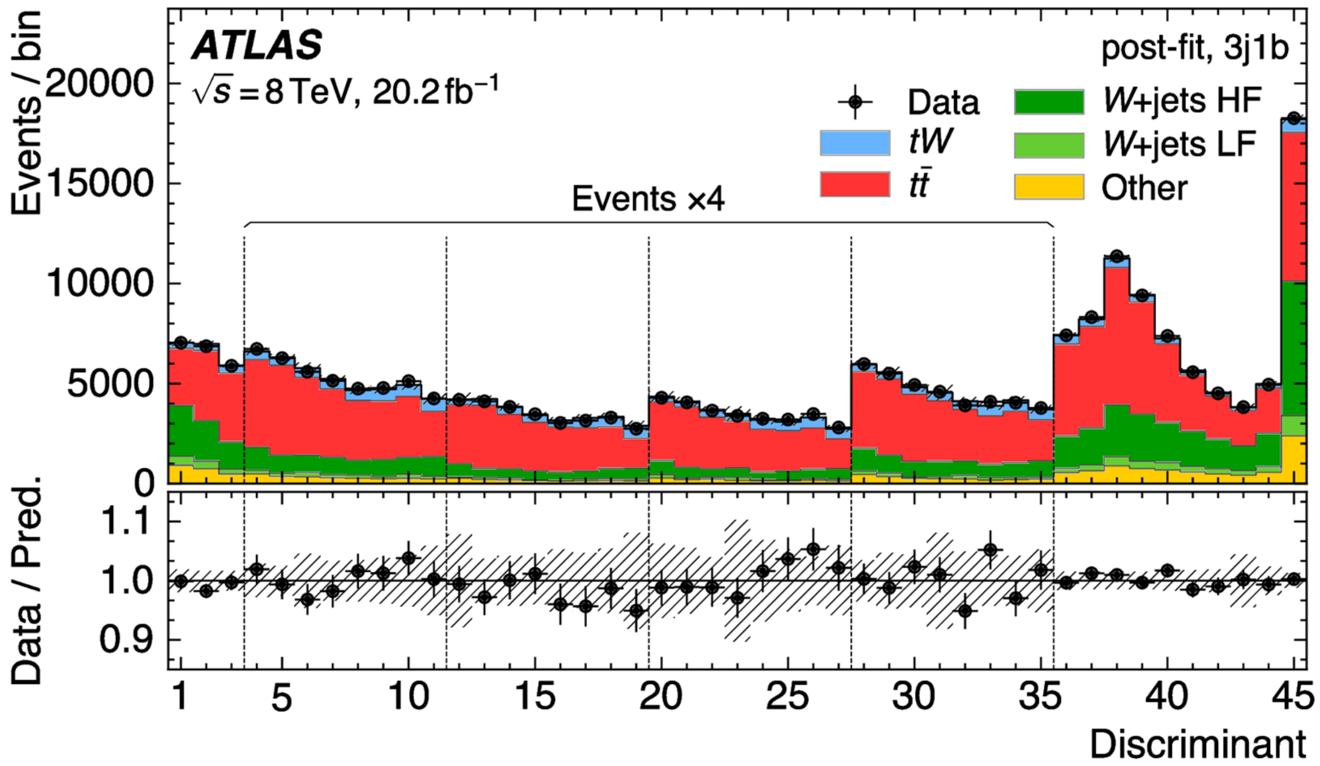
◦ Result is in good agreement with expectations at NLO+NNLL

$$\sigma_{\text{obs.}} = 26 \pm 7\text{pb}$$

$$\sigma_{\text{pred.}} = 22.4 \pm 1.5\text{pb}$$

Phys. Rev. D 60, 113006

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
$t\bar{t}$ 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
Model statistics	11
Data statistics	4
Total	27



- **Event selection**:
  - One energetic, isolated and central electron (> 30 GeV) or muon (> 26 GeV).
  - Veto of less energetic leptons (> 10 GeV muons, > 20 GeV electrons).
  - At least two and no more than four central and energetic jets should be in the events.
  - Exactly one of the jets must be b tagged.
- **Strategy**:
  - Events are categorised into separate regions depending on the number of jets.
  - Signal region: events with three jets (3j).
  - Control regions: events with two jets (2j; W+jets background CR) and events with four jets (4j; $t\bar{t}$ CR).
  - QCD/multijet background estimated from a dedicated region by inverting lepton isolation requirement.
  - W+jets background estimated by extrapolating to signal region the ratio with the QCD bkg. in the 2j0b region.
  - Two (for muon and for electron) MVA (BDTs) are trained in the signal region to discriminate.

Variable Description
Mass of the reconstructed Wboson decaying hadronically
Invariant mass of the b-tagged jet and sub-leading non b-tagged jet
Angular separation between the two non b-tagged jets
Angular separation between the reconstructed leptonic Wboson and leading non b-tagged jet
Transverse momentum of the selected lepton
Energy of the two non b-tagged jets system
Angular separation between the b-tagged jet and the selected lepton
Transverse momentum of the system made of the three jets, lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$

Measurement of tW production (semileptonic channel)

13 TeV, 35.9 $\mathbf{fb}^{-1}$, tW channel

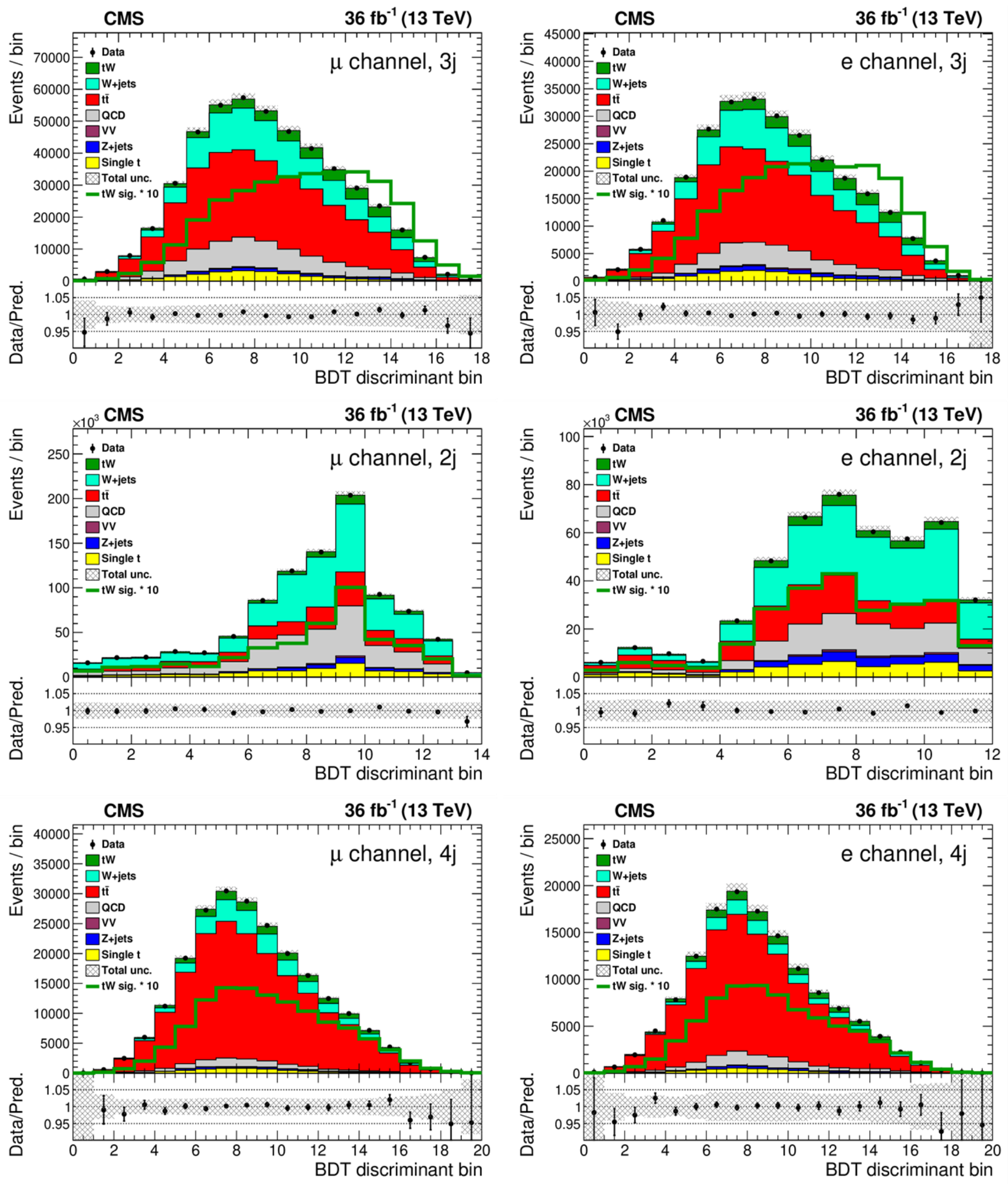
Sub. to JHEP, arXiv:2109.01706

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

PoS DIS2015 (2015) 170 | NNLO (QCD) | $\sigma_{\text{pred.}} = 71.7 \pm 1.8(\text{scale}) \pm 3.4(\text{PDF})\text{pb}$

JHEP 2021, 278 (2021) | N[3]LO (QCD) | $\sigma_{\text{pred.}} = 79.5^{+1.9}_{-1.8}(\text{scale})^{+2.0}_{-1.4}(\text{PDF})\text{pb}$

Source	Relative uncertainty (%)
Experimental	
Jet energy scale	6
b tagging efficiency	4
Luminosity	3
Lepton energy scale	2
Trigger efficiency	1
Jet energy resolution	1
b tagging misidentification rate	<1
Unclustered energy	<1
Pileup	<1
Normalization	
QCD multijet normalization	7
W+jets normalization	6
Z+jets normalization	3
Single t normalization	1
$t\bar{t}$ normalization	1
VV normalization	<1
Theoretical	
h_{damp}	4
Diagram removal/diagram subtraction	3
Underlying event tune	3
Colour reconnection model	1
Parton distribution function	1
Matrix element/parton shower matching	1
Final-state radiation	<1
Initial-state radiation	<1
Total systematic uncertainty	14
Statistical uncertainty	5
Total uncertainty	15



Summary

- The latest measurements from single top processes have been made in the **t** and **tW channels** as well as in the **tZq process**.
- The t-channel has been used to measure the top quark polarisation vector, differential cross sections depending on angular observables and also to put bounds on the tWb operator.
- This production mode has served to measure the top quark CKM elements in different contexts (both SM and BSM).
- A measurement in the tZq process has been made, with a final inclusive cross section with a ~15% relative uncertainty by ATLAS…
- …and another one by CMS with ~12% relative uncertainty, that also measured differentially the process depending on various observables, and measured the top quark spin asymmetry, everything in overall agreement with SM expectations.
- The tW channel in its semileptonic decay mode has been measured inclusively at 13 TeV and 8 TeV by CMS and ATLAS with 15% and 27% relative uncertainty respectively.

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CMS
Compact Muon Solenoid

ATLAS EXPERIMENT

Thanks for your attention