Most recent single top measurements at the LHC

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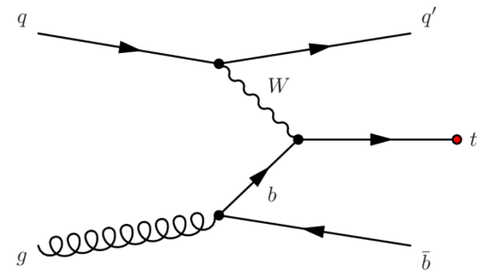
Single top-quark production at the LHC

- Top quark
  - most massive particle in the Standard Model
  - charge 2/3e, spin 1/2
  - decays almost exclusively to Wb
  - produced in pairs by strong and singly by weak interactions

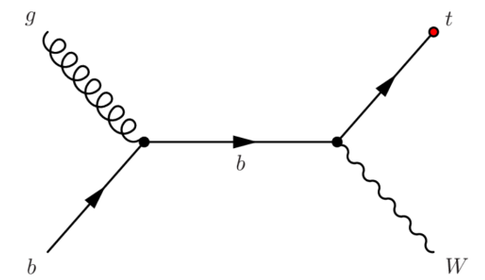
- Study of **single** top-quark production and decay:
  - allows to **test Standard Model**
    - e.g. top-quark couplings, including t-γ and t-Z
  - helps **improving** knowledge on **PDFs**
    - e.g. cross-section ratio $R_t = \sigma(t)/\sigma(\bar{t})$, sensitive to u/d-quark ratio in PDF sets
  - allows for **measurements** of top quark **properties**
    - e.g. top quark polarisation and mass

t-channel



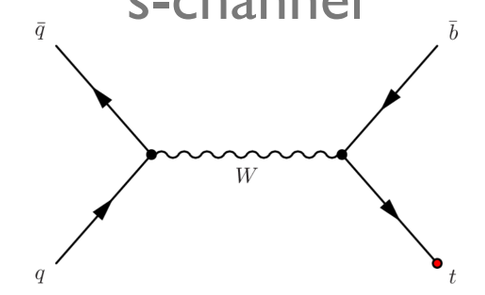
$\sigma_{t-\mathrm{ch}}(13\ \mathrm{TeV}) = 217.0^{+9.0}_{-7.7}\ \mathrm{pb}$

tW channel



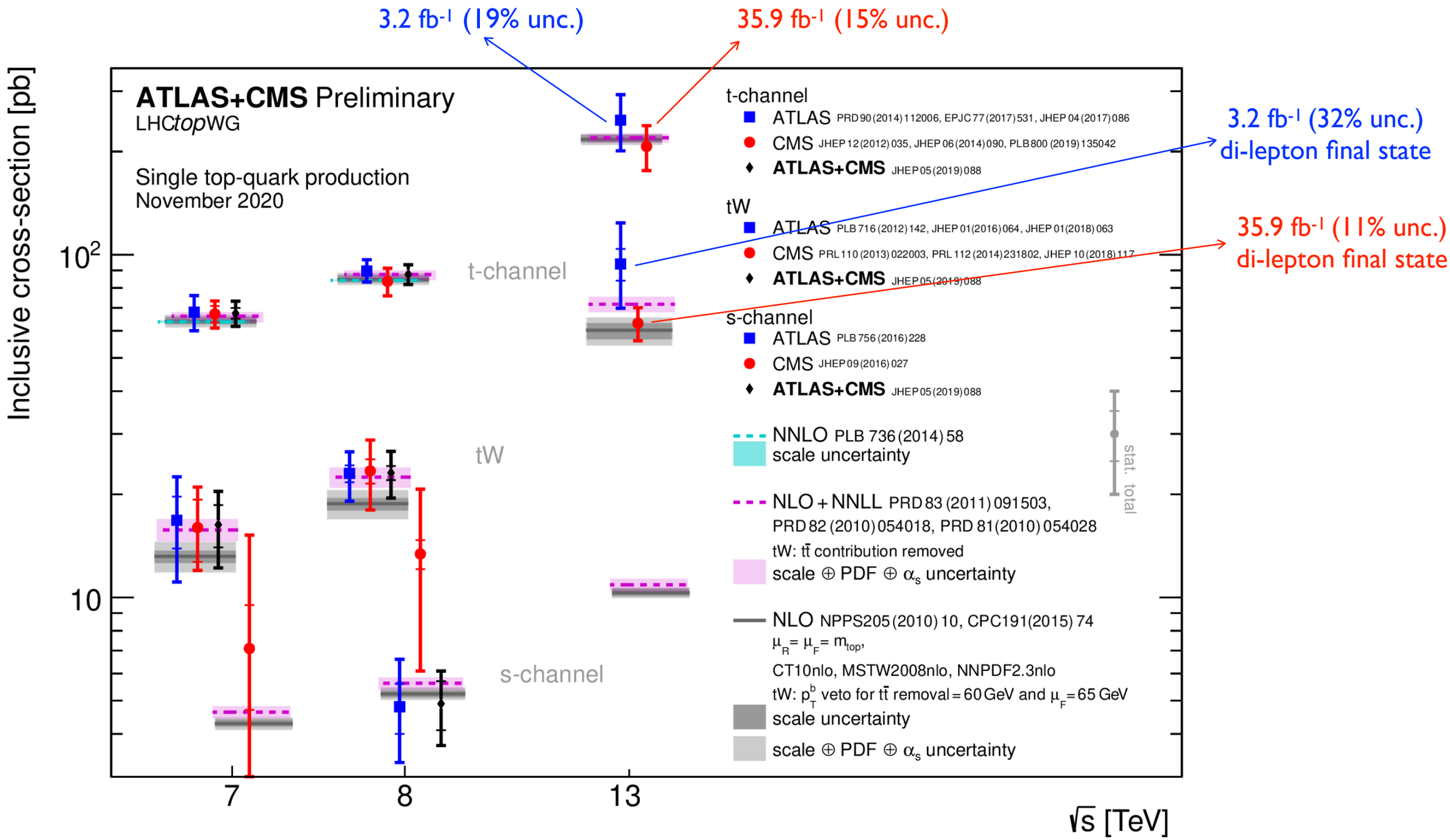
$\sigma_{tW}(13\ \mathrm{TeV}) = 71.7 \pm 3.8\ \mathrm{pb}$

s-channel



$\sigma_{s-\mathrm{ch}}(13\ \mathrm{TeV}) = 10.3 \pm 0.4\ \mathrm{pb}$

Run1 & 2 single-top cross-section measurements

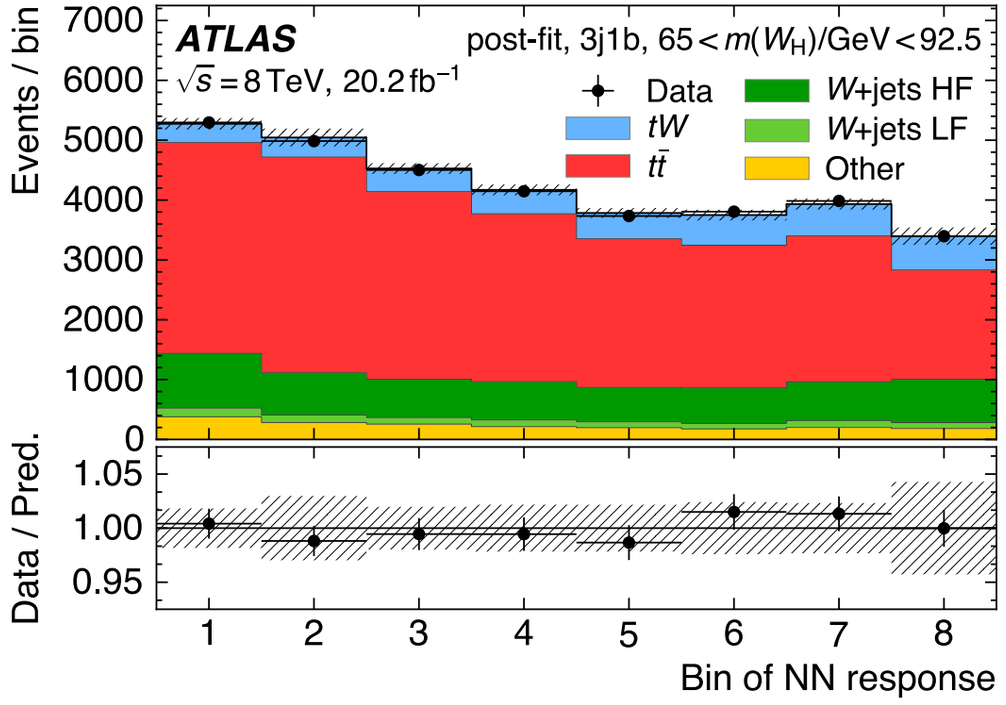


- Several **differential** cross-section **measurements** performed too
  - See talk by Oliver Majersky

tW measurements

- tW usually studied in **di-lepton** channel
  - Lower branching ratio but better signal/background
  - First observations by ATLAS [JHEP 01 (2016) 064] and CMS [PRL 112 (2014) 231802] at 8 TeV
  - Precise (~11%) inclusive cross section and first differential measurements

- tW in **single-lepton** channel
  - Higher branching ratio but worse signal/background
  - Allows for complete W and top-quark kinematics reconstruction
  - ATLAS measured tW cross-section with 20.2 fb^{-1} at 8 TeV
    - observed significance: 4.5σ [EPJC 81 (2021) 720]



Observation of tW in single-lepton channel

- Measurement with 36 fb^{-1} at 13 TeV
- tW modelled with DR scheme
- Signature:
  1 e/μ, 3 jets (1 b-tagged), E_T^{miss}
- Main backgrounds
  - $t\bar{t}$
  - W+jets
    → shape from simulation, normalisation from data
  - QCD multijet
    → both shape and normalisation from data

- 3j1b SR
  + 2j1b W+jets/multijet CR + 4j1b $t\bar{t}$ CR

- BDT trained to separate tW from $t\bar{t}$ background

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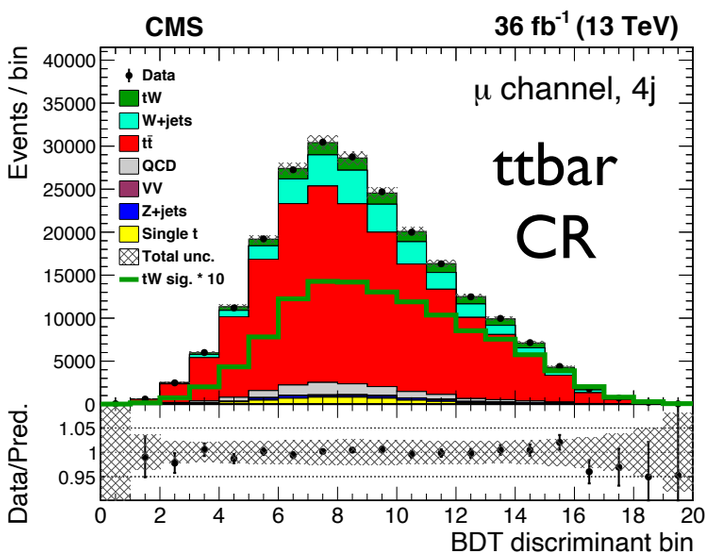

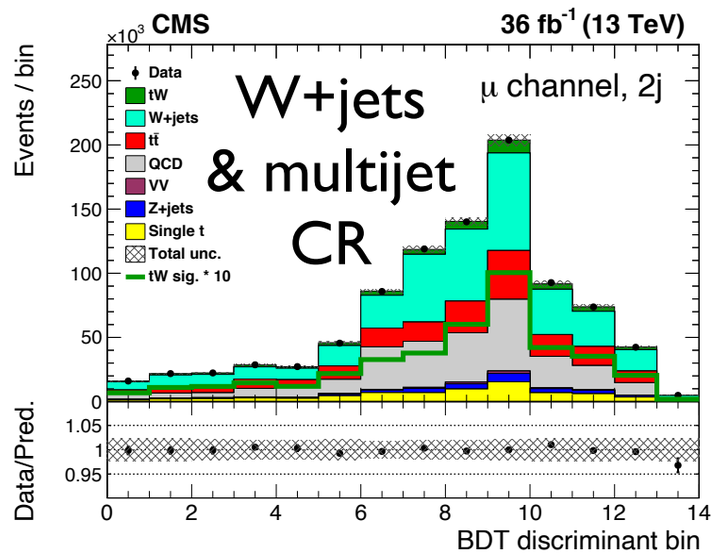

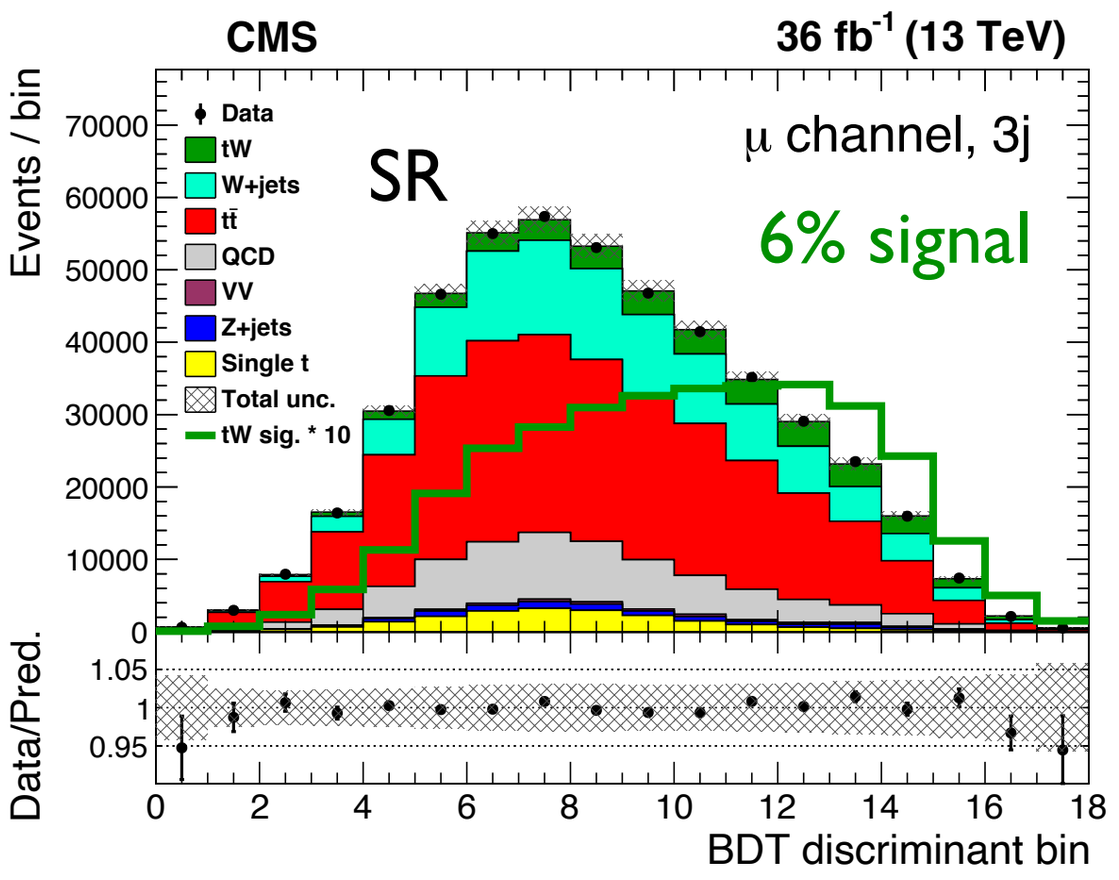

Observation of tW in single-lepton channel

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

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- Simultaneous fit of BDT discriminant in SR and CRs
- tW measured cross section:

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

15% unc.

- In agreement with predictions:

$$\sigma_{tW}(\mathrm{NNLO}) = 71.7 \pm 1.8\ (\mathrm{scale}) \pm 3.4\ (\mathrm{PDF})\ \mathrm{pb}$$

arXiv:1506.04072

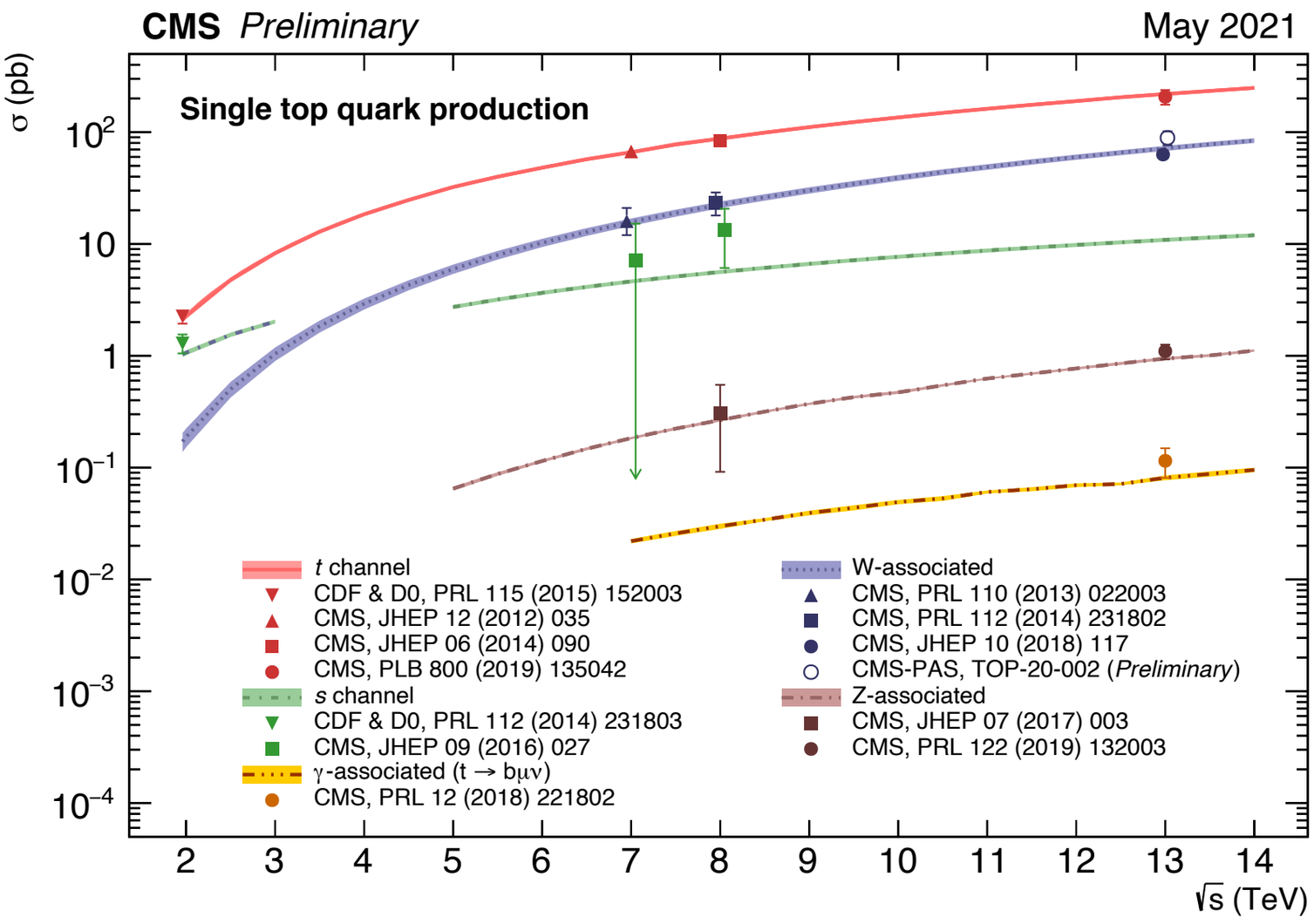
$$\sigma_{tW}(\mathrm{aN^3LO}) = 79.5\ ^{+1.9}_{-1.8}\ (\mathrm{scale})\ ^{+2.0}_{-1.4}\ (\mathrm{PDF})\ \mathrm{pb}$$

arXiv:2102.11300

- Signal significance exceeding 5σ
- **First observation** of tW in **single-lepton** channel

Rare single top-quark production at the LHC

- With Run2
  rare single top-quark production processes available for the first time
- Fundamental to probe top-quark EW couplings
- Exploring **t-channel** productions
  - tZq observed by both ATLAS and CMS
  - evidence of tqγ production by CMS



Single top + γ production

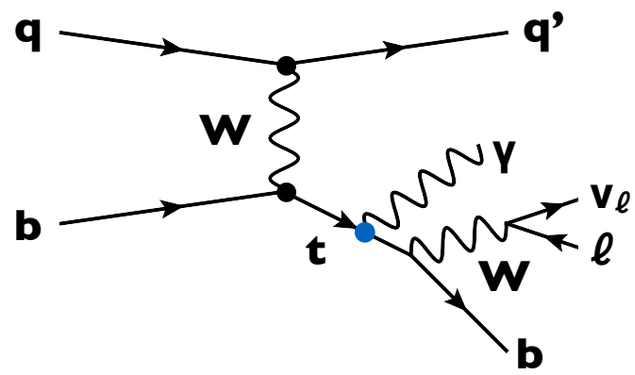
- Single top + γ not observed yet

- Fiducial space (ATLAS) at parton level
  $p_T(\gamma) > 20$ GeV, $|\eta(\gamma)| < 2.37$,
  $\Delta R(\gamma, X) > 0.4$,
  $|\eta(\ell)| < 2.5$
  - slightly different for CMS
- Cross-section
  NLO QCD, 4FS, scale $H_T/2$

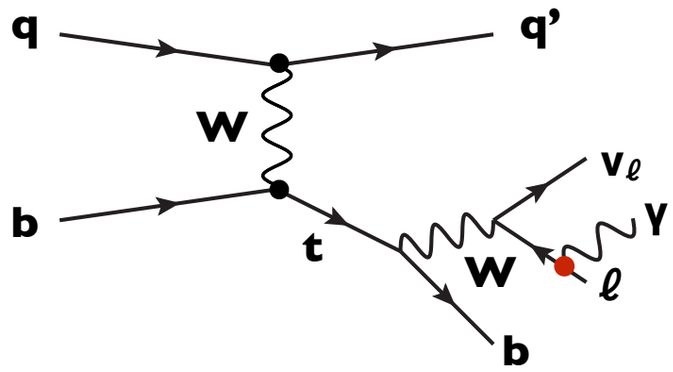
$$\sigma_{tq\gamma} \times \mathcal{B}(t \to \ell\nu b) = 406^{+25}_{-32} \text{ fb}$$

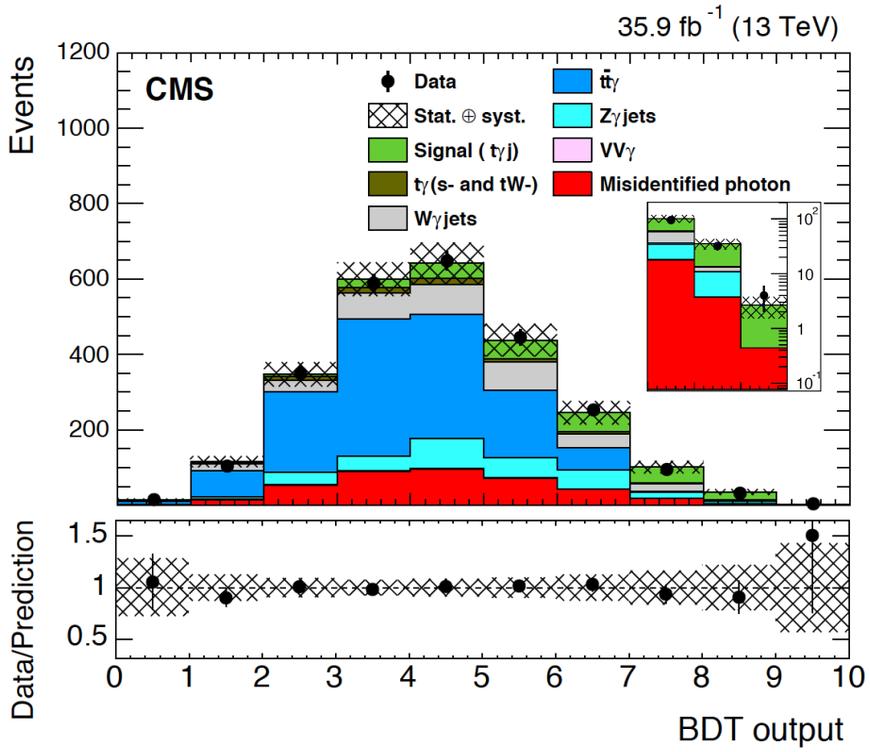
- CMS found evidence of tqγ production with 35.9 fb^{-1} at 13 TeV
  - observed significance: 4.4σ
    [PRL 121 (2018) 221802]

$tq\gamma$ production



γ from top decay : $t \to \ell\nu b\gamma$





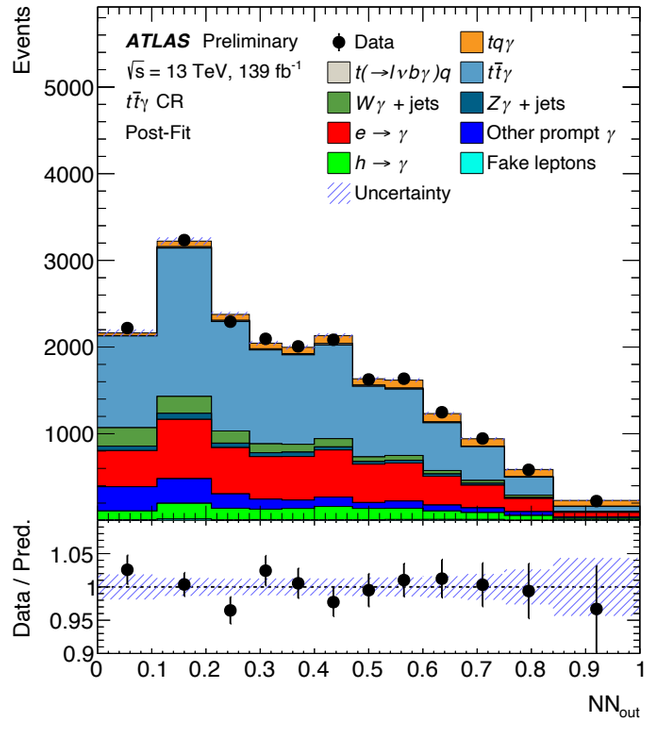
Observation of single top + γ production

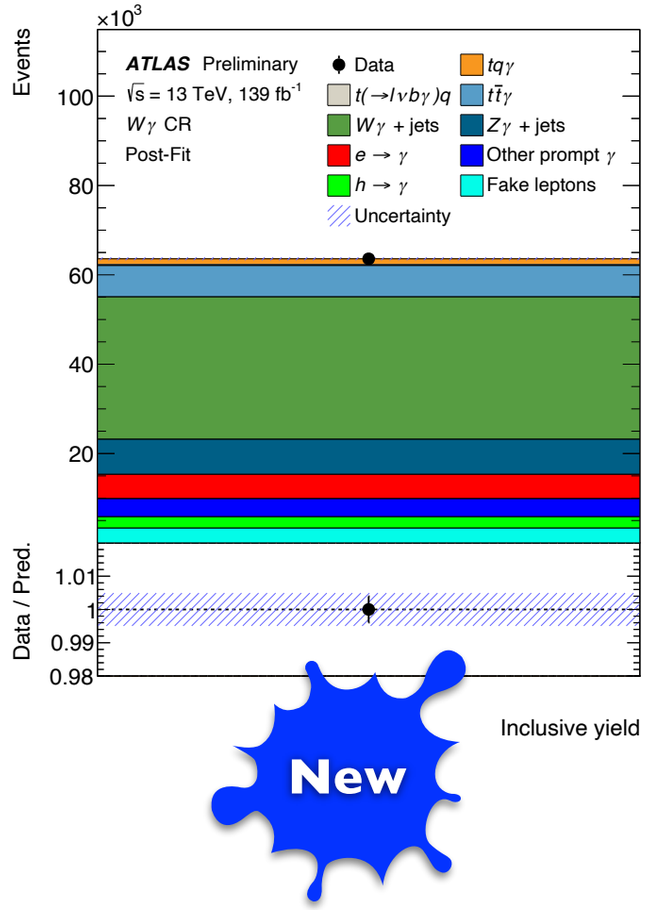
- Search with 139 fb^{-1} at 13 TeV
- Signature:
  1 γ, 1 e/μ, 2 jets (1 b-tagged), E_T^{miss}
- Main backgrounds
  - $t\bar{t}\gamma$
  - Wγ+jets
  - e→γ fakes

  → mostly di-leptonic $t\bar{t}$, data/MC scale factors using ee and eγ events close to m_Z

- 0fj and ≥1fj SRs (based on t-channel forward jet)
  + $t\bar{t}\gamma$ CR (1 tight + 1 loose b-tags)
  + Wγ CR (1 loose b-tag)

- NNs trained in SRs with 12/15 inputs
  based on final-state kinematics and b-tag properties





[ATLAS-CONF-2022-013]

Observation of single top + γ production

ATLAS-CONF-2022-013

New

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modelling	±5.6%
Background MC statistics	±3.5%
$t\bar{t}$ modelling	±3.4%
$tq\gamma$ MC statistics	±3.4%
$t\,(\to \ell\nu b\gamma)\,q$ modelling	±1.9%
Additional background uncertainties	±1.9%
$tq\gamma$ modelling	±1.8%
$t\,(\to \ell\nu b\gamma)\,q$ MC statistics	±0.3%
Lepton fakes	±2.2%
$h \to \gamma$ photon fakes	±2.2%
$e \to \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.2%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±4.0%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.8%
Total systematic uncertainty	±10.9%

- Simultaneous fit of NN output in SRs and $t\bar{t}\gamma$ CR, total yield in Wγ CR
- Statistical uncertainty: 3%
- Systematic uncertainty: 11%
  - $t\bar{t}\gamma$ and $t\bar{t}$ modelling
  - MC statistics, both $t\bar{t}$ and tqγ
  - jets

Observation of single top + γ production

New

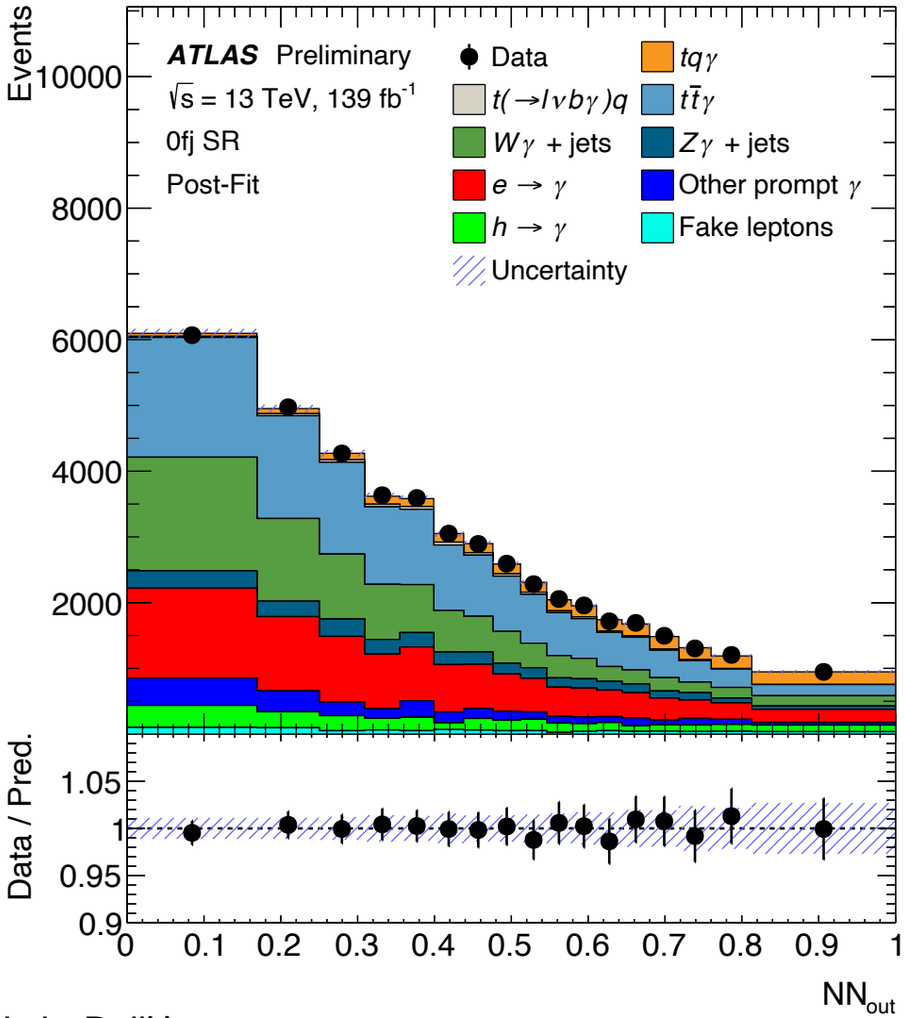
- First observation of tqγ: 9.1σ (6.7σ) observed (expected) significance
- Parton-level fiducial cross section

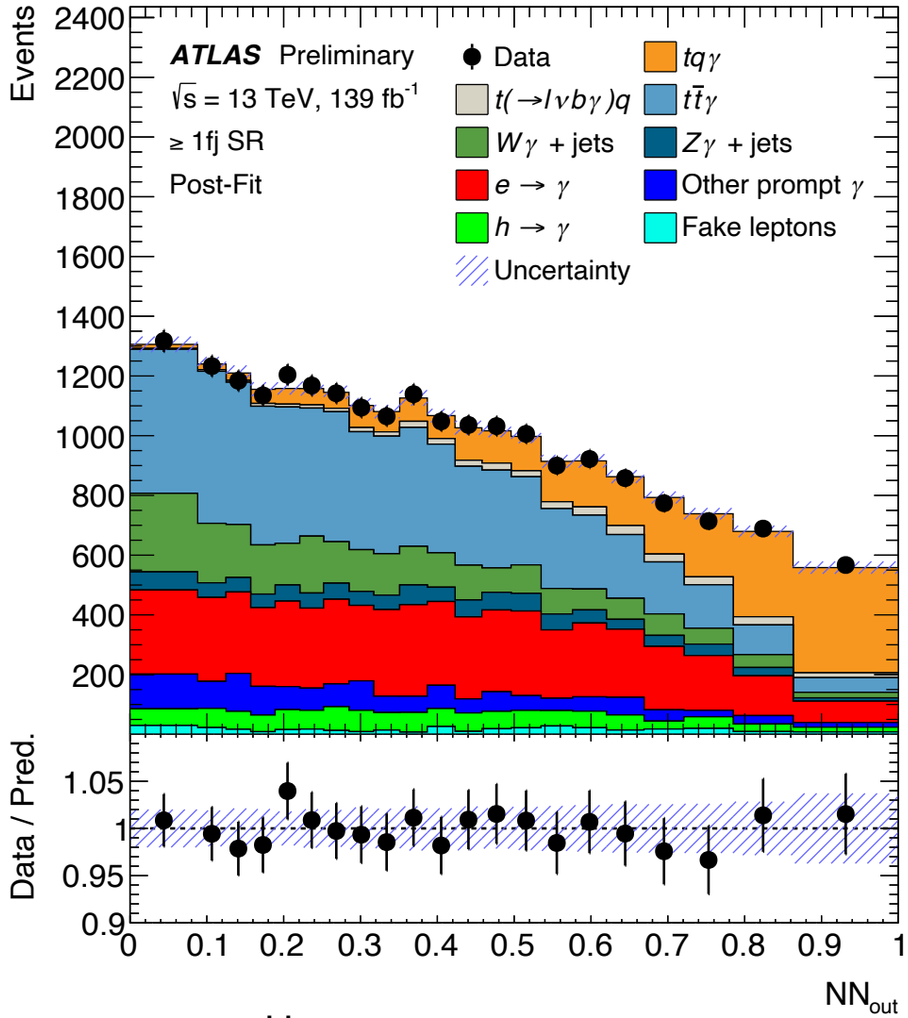
$$\sigma_{tq\gamma} \times \mathcal{B}(t \to \ell\nu b) = 580 \pm 19\ (\text{stat.}) \pm 63\ (\text{syst.})\ \text{fb}$$

11% unc.

- Particle-level fiducial cross section

$$\sigma_{tq\gamma} \times \mathcal{B}(t \to \ell\nu b) + \sigma_{t(\to \ell\nu b\gamma)q} = 287 \pm 8\ (\text{stat.}) \pm 31\ (\text{syst.})\ \text{fb}$$





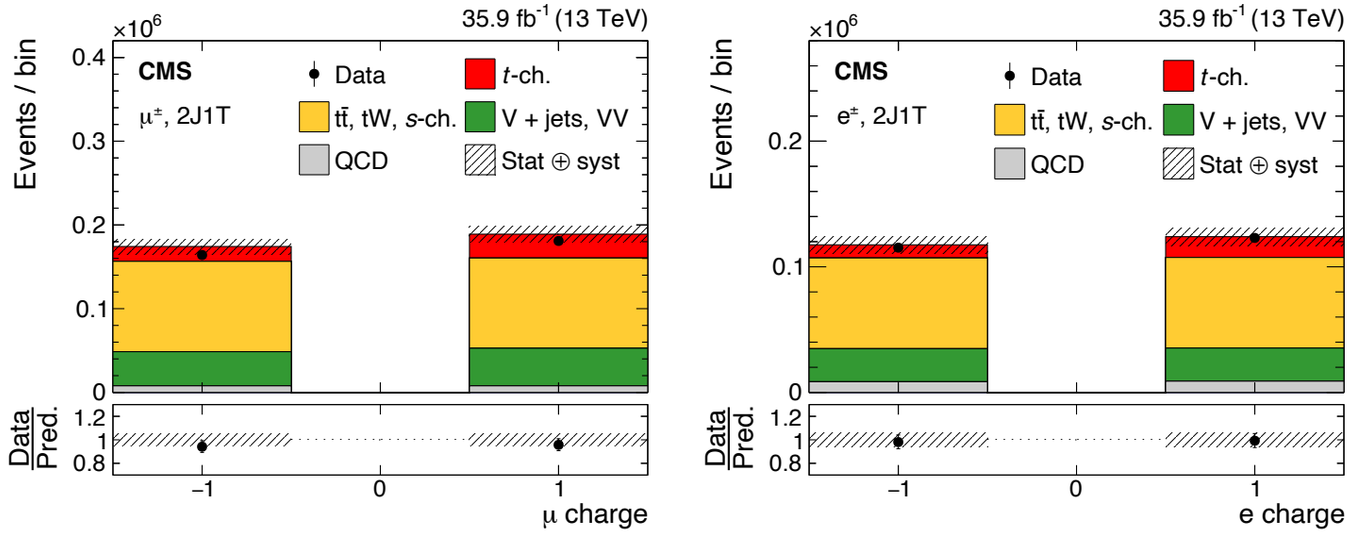
~40% higher measured cross-sections

Compatibility 2.5σ/1.9σ at parton/particle level

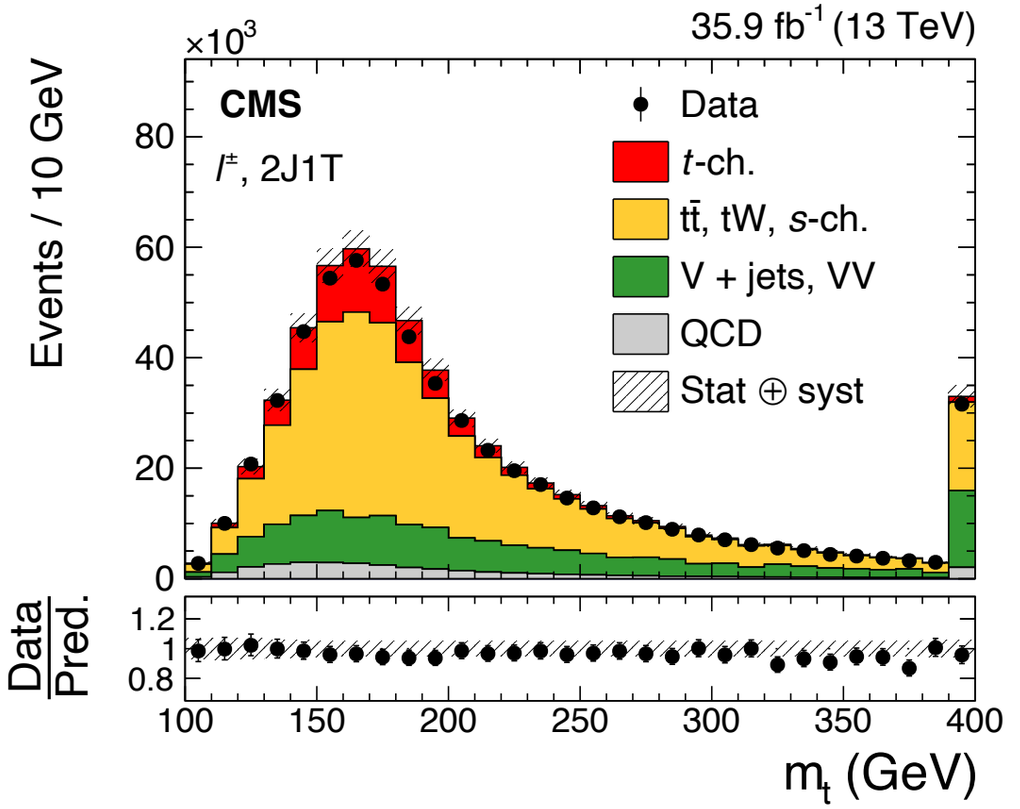
ATLAS-CONF-2022-013

Measurement of m_t in single-top events

- Measurement
  with 35.9 fb^{-1} at 13 TeV
- Signature:
  1 e/μ, 2 jets (1 b-tagged), E_T^{miss}
- Main backgrounds
  - $t\bar{t}$
  - W+jets
  - multijets
- Top quark mass reconstruction
  - Unknown longitudinal momentum of neutrino extracted using m_W constraint, giving two solutions
    - If both real, retain lowest value
    - If complex solutions, set radical to 0 → get two couples of neutrino p_x and p_y → choose pair resulting in neutrino p_T with lowest $\Delta\varphi$ with E_T^{miss}



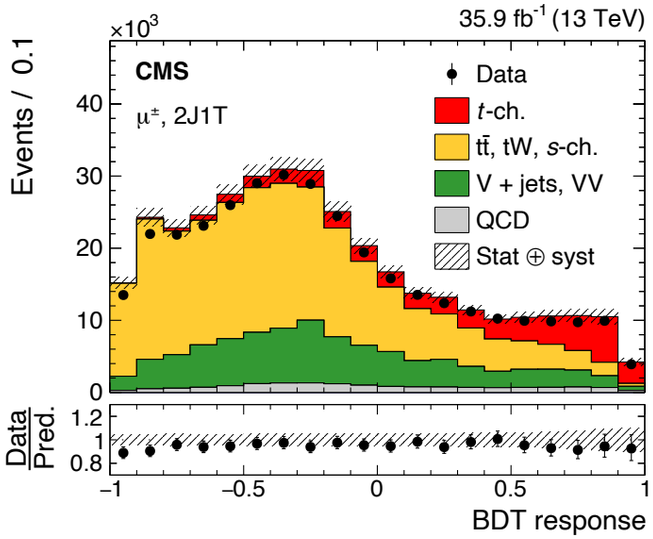
$$m_{\mathrm{W}}^2 = \left(E_\ell + \sqrt{(p_{\mathrm{T}}^{\mathrm{miss}})^2 + p_{z,\nu}^2}\right)^2 - (\vec{p}_{\mathrm{T},\ell} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}})^2 - (p_{z,\ell} + p_{z,\nu})^2$$

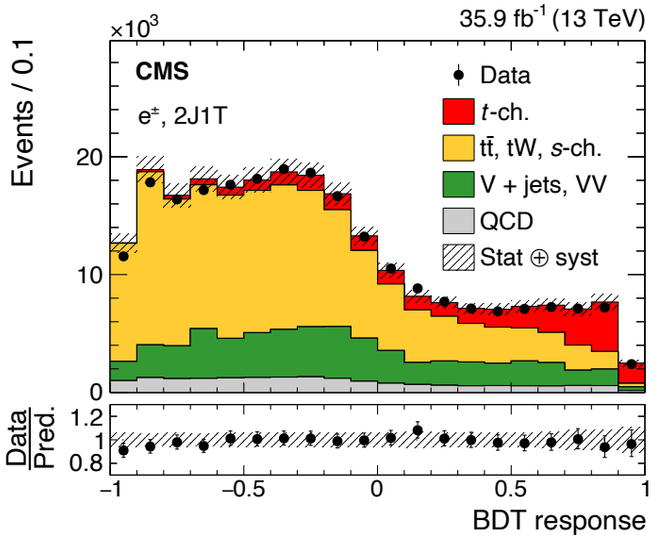


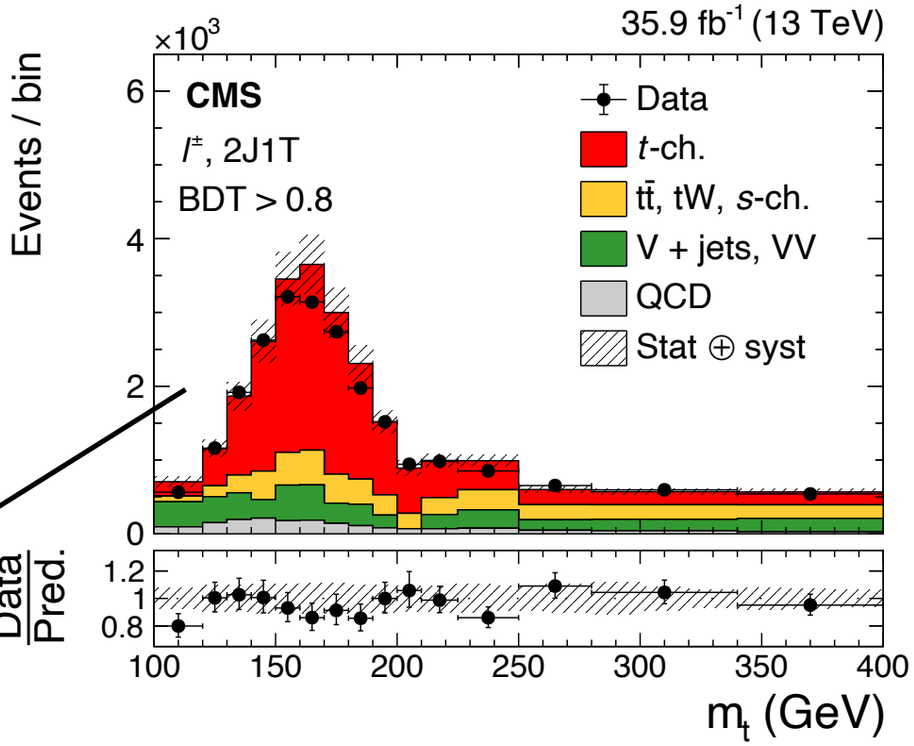
Measurement of m_t in single-top events

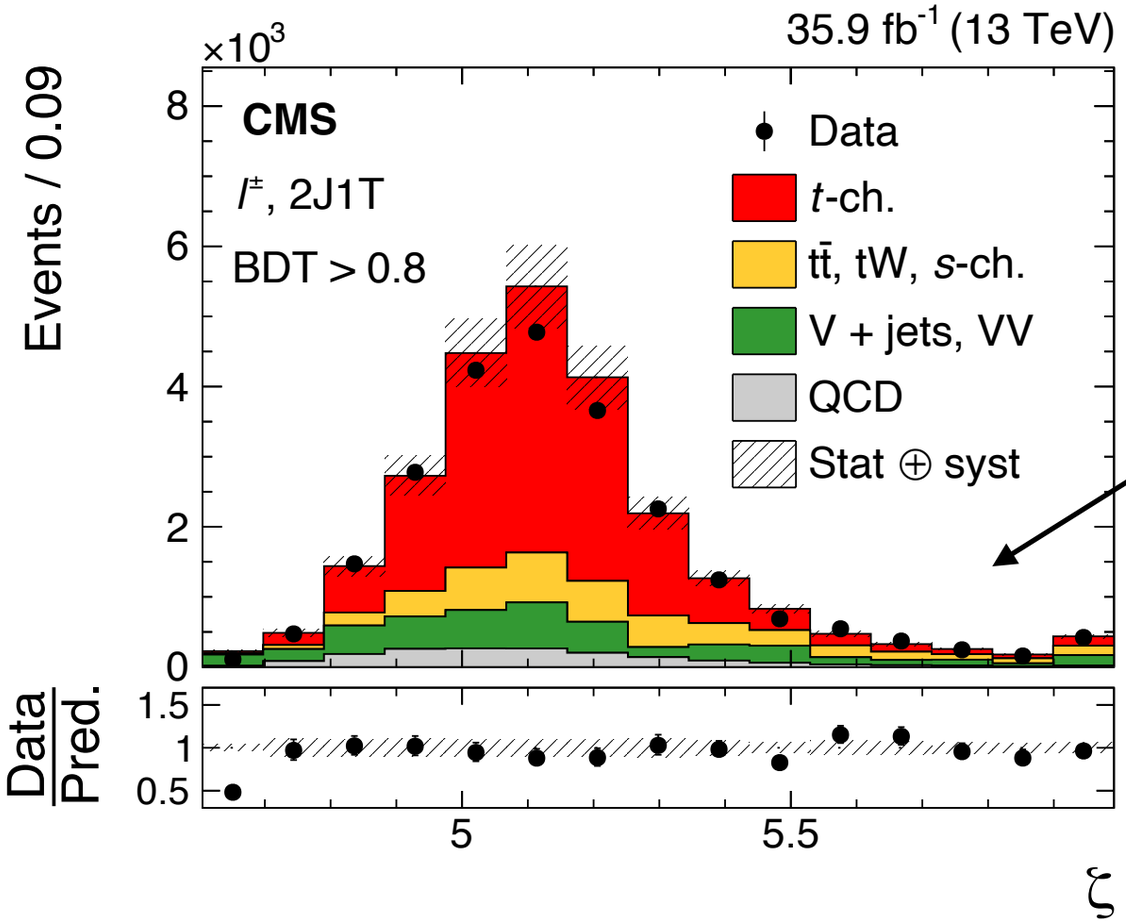
- BDT trained to separate t-channel from all backgrounds
  - BDT > 0.8 with 65 (60)% signal purity for μ(e)
- Since m_t distribution highly skewed, use natural logarithm

$$\xi = \ln(m_t/1\ \text{GeV})$$









- Max. likelihood fit of ξ
  - Multijet contribution subtracted

Measurement of m_t in single-top events

	Source		$\delta m_{l^\pm}$	δm_{l^+}	δm_{l^-}
	Statistical		±0.19	±0.23	±0.33
	Statistical + profiled systematic		±0.32	±0.37	±0.58
Experimental	JES	Correlation group intercalibration	±0.09	±0.07	±0.12
		Correlation group MPFInSitu	±0.02	±0.02	±0.01
		Correlation group uncorrelated	±0.39	±0.17	±0.83
		Total (quadrature sum)	±0.40	±0.18	±0.84
	JER		<0.01	<0.01	<0.01
	Unclustered energy		<0.01	<0.01	<0.01
	Muon efficiencies		<0.01	<0.01	<0.01
	Electron efficiencies		±0.01	±0.01	±0.01
	Pileup		±0.14	±0.04	±0.34
	b tagging		±0.20	±0.18	±0.22
	QCD multijet background		±0.02	±0.01	±0.02
	Mass calibration		±0.11	±0.13	±0.20
	Int. luminosity		<0.01	<0.01	±0.01
	CR model and ERD		±0.24 (0.017)	±0.39 (0.027)	±0.68 (0.048)
	Flavor-dependent JES	Gluon	$+0.52$	$+0.75$	-0.03
		Light quark (uds)	-0.18	$+0.18$	-0.23
		Charm	$+0.01$	$+0.08$	$+0.11$
		Bottom	-0.48	-0.29	-0.31
		Total (linear sum)	-0.13	$+0.72$	-0.46
Modelling	b quark hadronization model	b frag. Bowler–Lund	±0.03	±0.06	±0.08
		b frag. Peterson	$+0.14$	$+0.11$	$+0.19$
		Semileptonic b hadron decays	±0.18	±0.17	±0.19
		Total (quadrature sum)	$+0.23\ -0.18$	$+0.21\ -0.18$	$+0.28\ -0.21$
	Signal modeling	ISR	±0.01	±0.01	<0.01
		FSR	±0.28	±0.31	±0.20
		μ_R and μ_F scales	±0.09	±0.13	±0.03
		PDF+α_S	±0.06	±0.06	±0.07
		Total (quadrature sum)	±0.30	±0.34	±0.21
	$t\bar{t}$ modeling	ISR	±0.11 (0.008)	±0.02 (0.001)	±0.22 (0.016)
		FSR	±0.10 (0.007)	±0.14 (0.010)	±0.40 (0.028)
		ME-PS matching scale	±0.10 (0.007)	±0.10 (0.006)	±0.10 (0.008)
		μ_R and μ_F scales	±0.03	±0.03	±0.01
		PDF+α_S	<0.01	<0.01	<0.01
		Top quark p_T reweighting	-0.04	-0.08	-0.04
		UE	±0.07 (0.005)	±0.04 (0.003)	±0.17 (0.012)
		Total (quadrature sum)	±0.20	$+0.18\ -0.20$	±0.50
	Parametric shapes	Signal shape	±0.05	±0.03	±0.04
		$t\bar{t}$ bkg. shape	±0.07	±0.04	±0.05
		EW bkg. shape	±0.03	±0.01	±0.02
		Total (quadrature sum)	±0.09	±0.05	±0.07
	Total externalized systematic		$+0.69\ -0.71$	$+0.97\ -0.65$	$+1.32\ -1.39$
	Grand total		$+0.76\ -0.77$	$+1.04\ -0.75$	$+1.44\ -1.51$

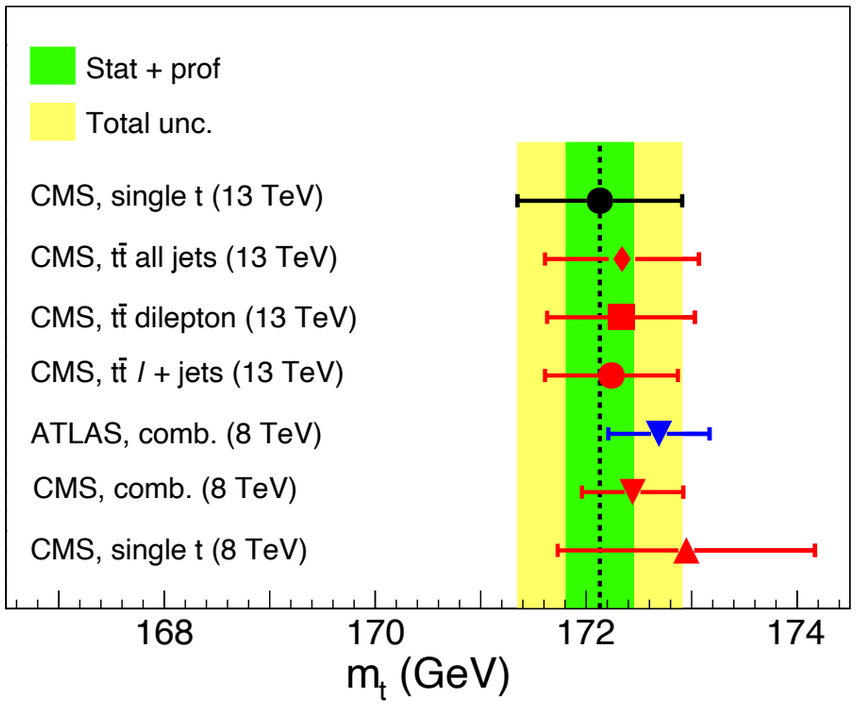
- Systematic uncertainties
  - profiled
    signal and background normalisations added as nuisance param.
  - externalised
    max. likelihood fit repeated with varied templates

- Larger systematic uncertainties for negatively charged lepton case due to higher background contributions

Measurement of m_t in single-top events

$$m_{\mathrm{t}} = 172.13 \pm 0.32\ (\mathrm{stat.} + \mathrm{prof.})\ ^{+0.69}_{-0.70}\ (\mathrm{ext.})\ \mathrm{GeV} = 172.13\ ^{+0.76}_{-0.77}\ \mathrm{GeV}$$

First **sub-GeV** total uncertainty for m_t from single-top events



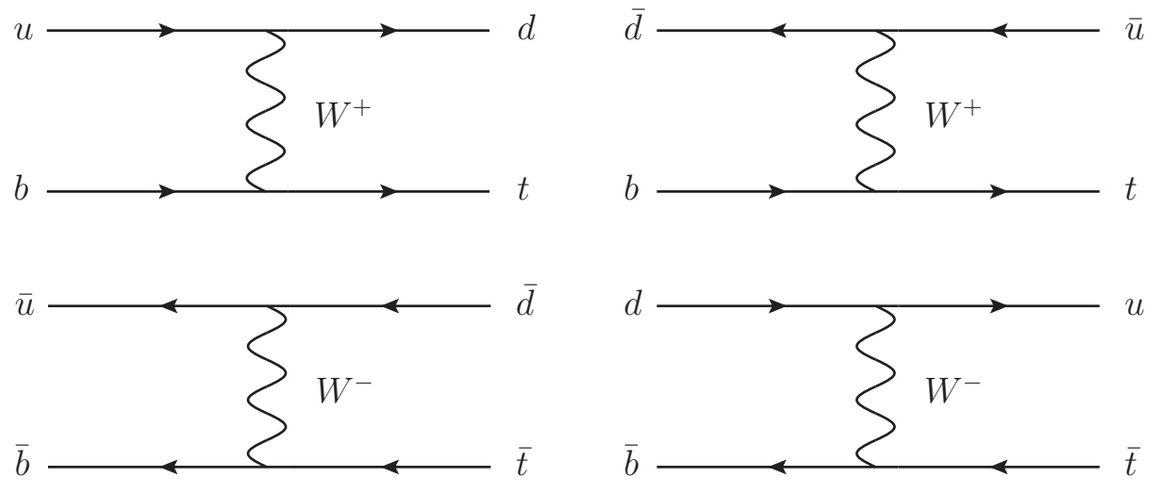
$$R_{m_{\mathrm{t}}} = \frac{m_{\bar{\mathrm{t}}}}{m_{\mathrm{t}}} = 0.9952 \pm 0.0040\ (\mathrm{stat.} + \mathrm{prof.})\ ^{+0.0068}_{-0.0096}\ (\mathrm{ext.}) = 0.9952\ ^{+0.0079}_{-0.0104}$$

$$\Delta m_{\mathrm{t}} = m_{\mathrm{t}} - m_{\bar{\mathrm{t}}} = 0.83 \pm 0.69\ (\mathrm{stat.} + \mathrm{prof.})\ ^{+1.65}_{-1.16}\ (\mathrm{ext.})\ \mathrm{GeV} = 0.83\ ^{+1.79}_{-1.35}\ \mathrm{GeV}$$

Consistent with non violation of **CTP** symmetry

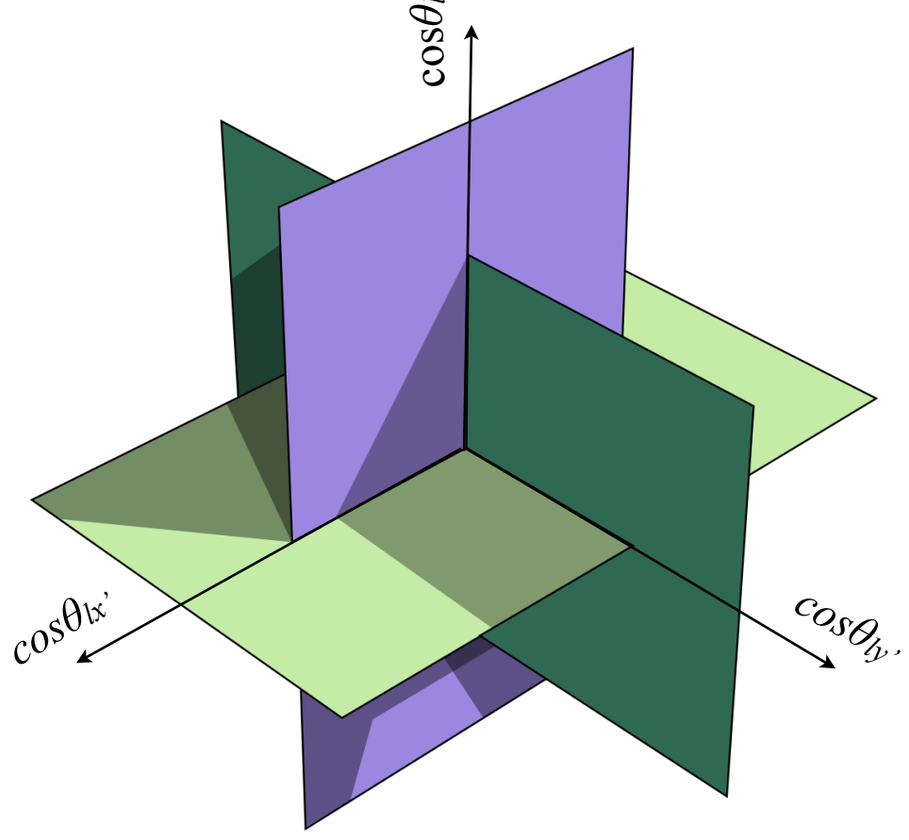
Top quark polarisation

- Top and anti-top quarks produced in t-channel highly polarised



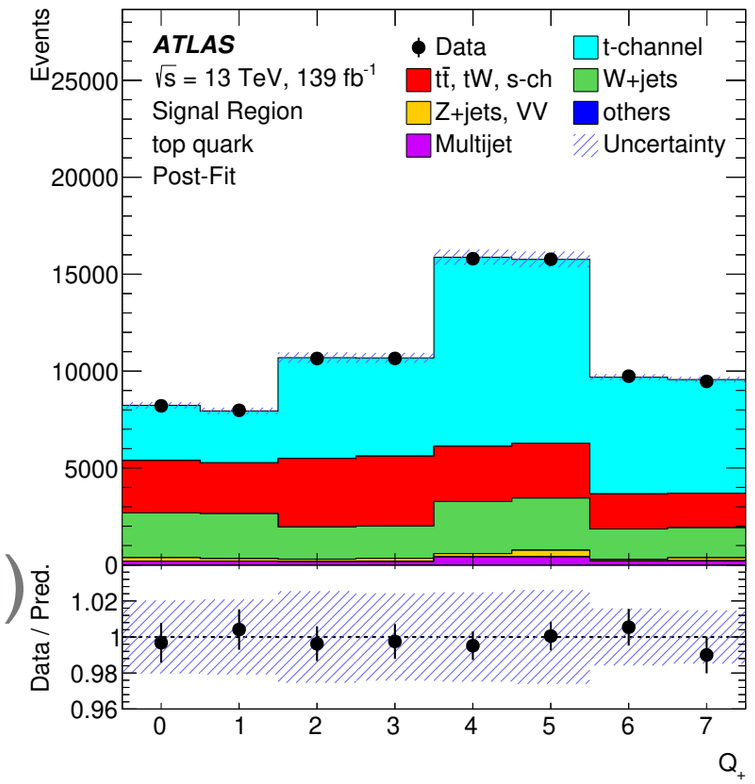
- Measurement with 139 fb^{-1} at 13 TeV
- Signature:
  1 e/μ, 2 jets (1 b-tagged), E_T^{miss}
  - S/B after selection in signal region: 0.94

- Profile likelihood fit in
  - 2 SRs (top & anti-top)
    - Octant variable Q
      slice phase space depending on the sign of $\cos\theta_j$
      $Q = 4 \cdot \Theta(\cos\theta_{\ell z'}) + 2 \cdot \Theta(\cos\theta_{\ell x'}) + \Theta(\cos\theta_{\ell y'})$
  - 2 CRs ($t\bar{t}$ and W+jets)
    - Lepton charge

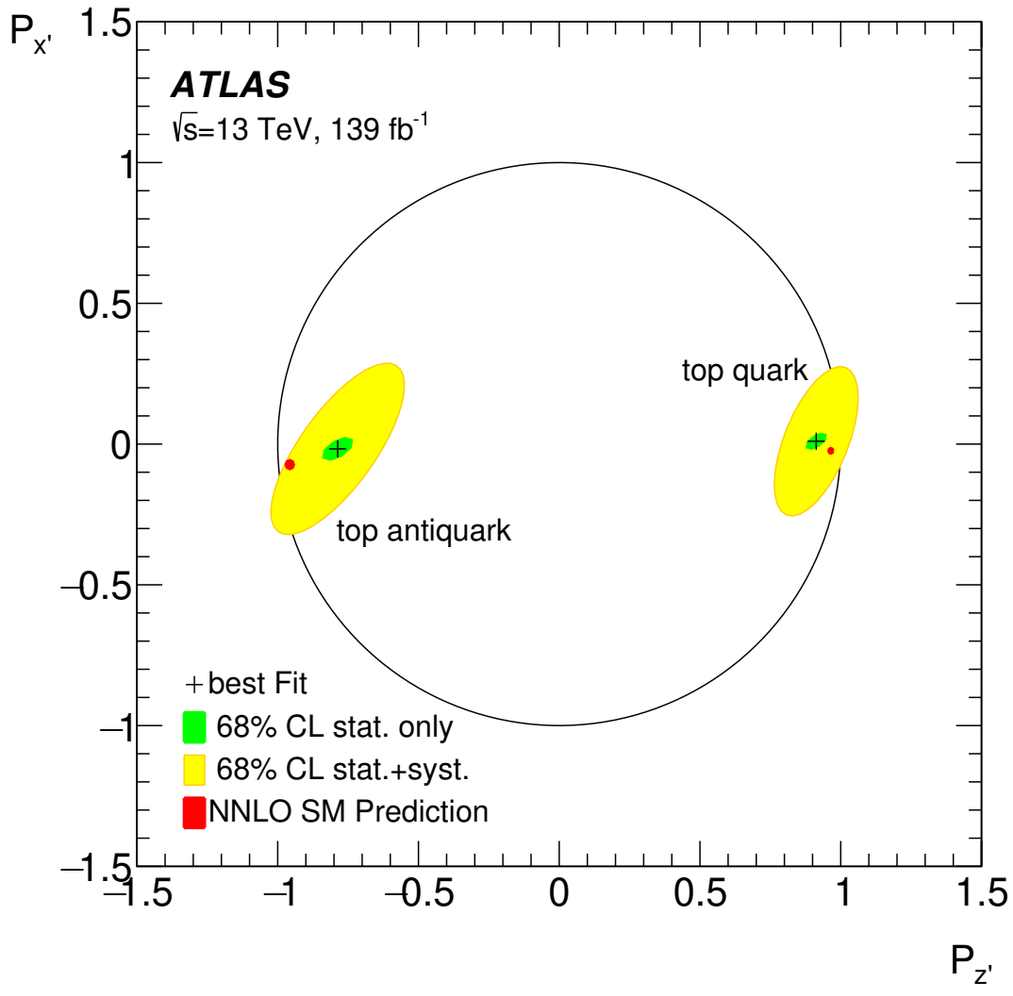


Top quark polarisation

- Simulated Protos+Pythia8 templates with fully polarised states used in the fit ($P_{x'}$, $P_{y'}$, $P_{z'}$ = ±1)
- Extract:
  - $P_{x',t}$, $P_{y',t}$, $P_{z',t}$, $P_{x',\bar{t}}$, $P_{y',\bar{t}}$, $P_{z',\bar{t}}$
  - 3 normalisations ($t\bar{t}$, W+jets & t-channel signal)



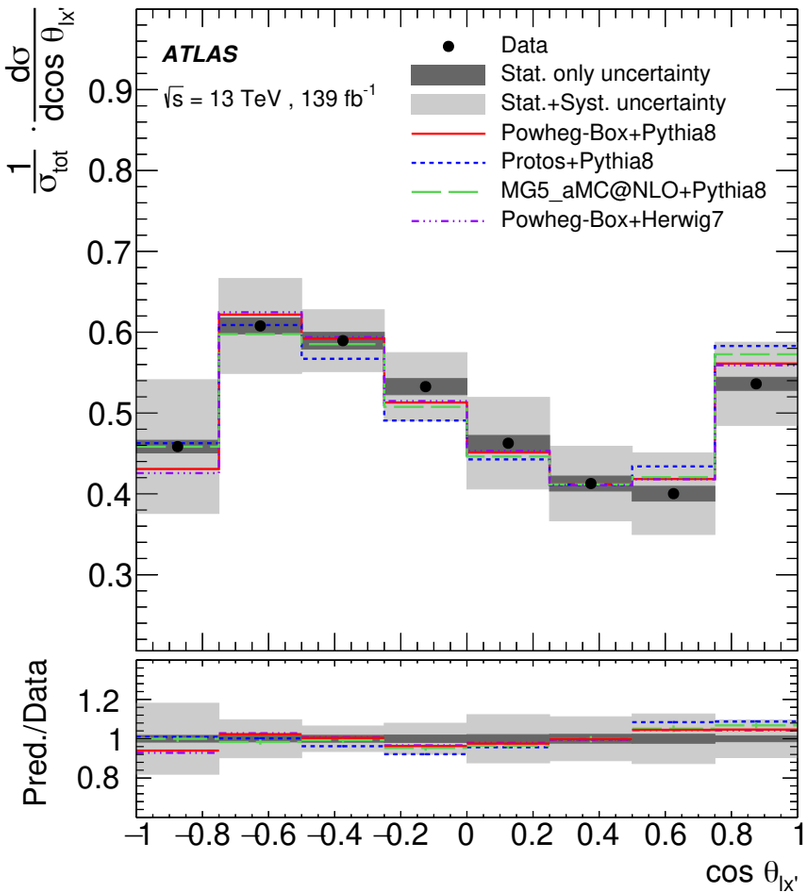
Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$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

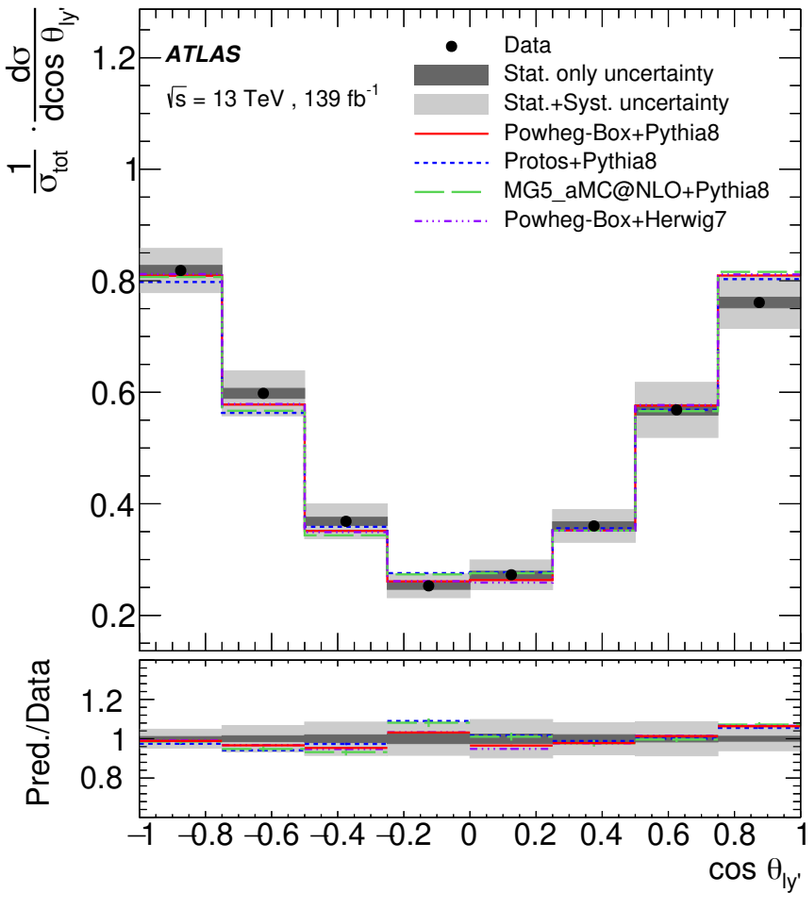


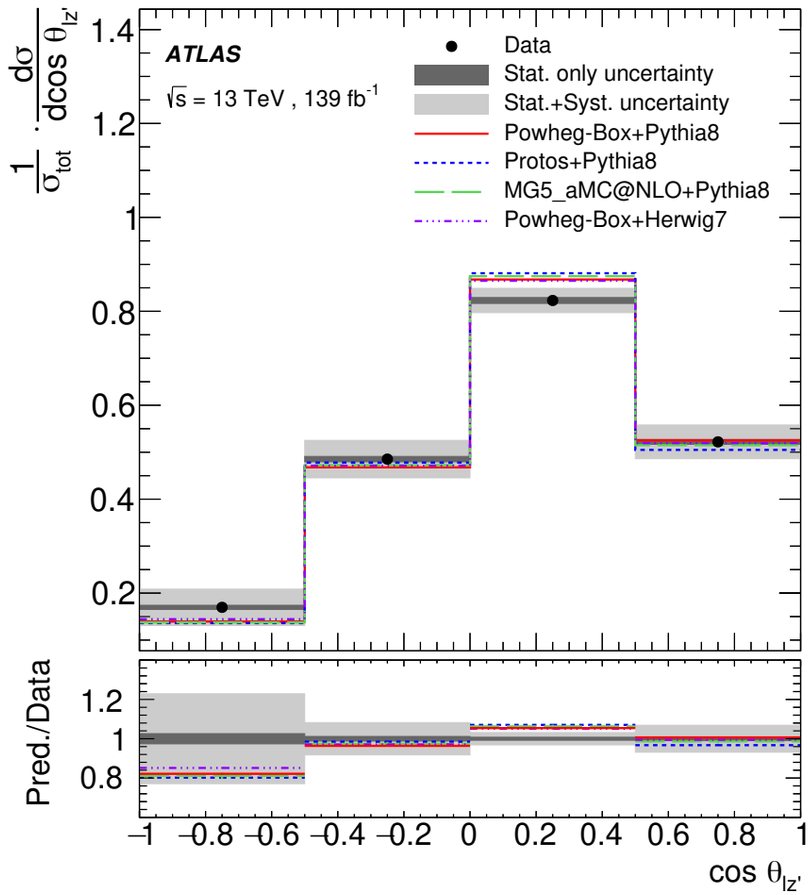
Good agreement with SM prediction

Top quark polarisation

- Normalised differential cross-section measurements
  - As a function of $\cos\theta_{lx'}$, $\cos\theta_{ly'}$, $\cos\theta_{lz'}$







- Results interpreted in EFT context to set limits on Wilson coefficients

Conclusions

- Measurement of single top-quark production both at precision and at observation level with Run1 and Run2 data
  - observation of tW in single-lepton channel with 36 fb^{-1} at 13 TeV by CMS
- Rare single top-quark processes becoming accessible with Run2
  - tZq observed by both ATLAS and CMS
  - observation of tqγ with 139 fb^{-1} at 13 TeV by ATLAS
  - tHq and tWZ next in line
- Top-quark properties being studied in single top-quark t-channel production
  - measurement of top polarisation by ATLAS with 139 fb^{-1} at 13 TeV
  - measurement of top mass by CMS with 36 fb^{-1} at 13 TeV

- Dear Run3, hope to see you soon with more data!

BackUp

Observation of tW in single-lepton channel

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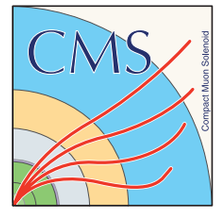
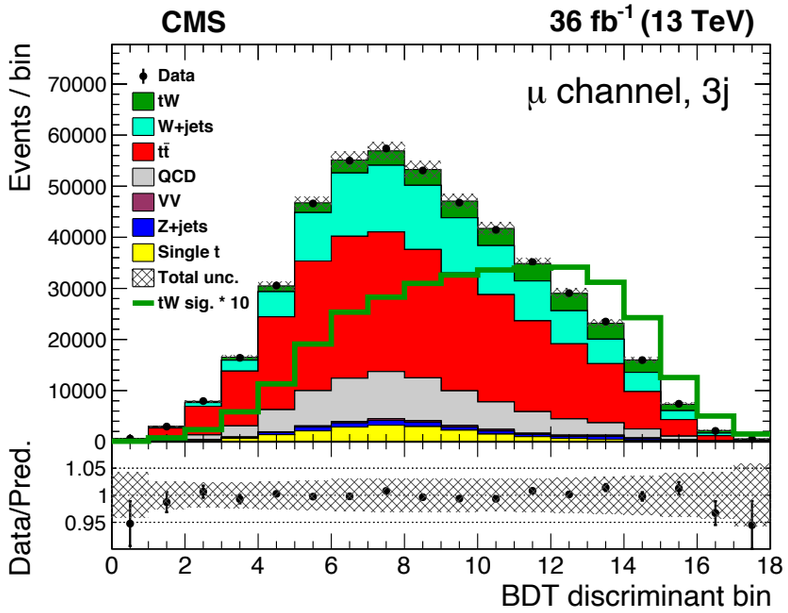
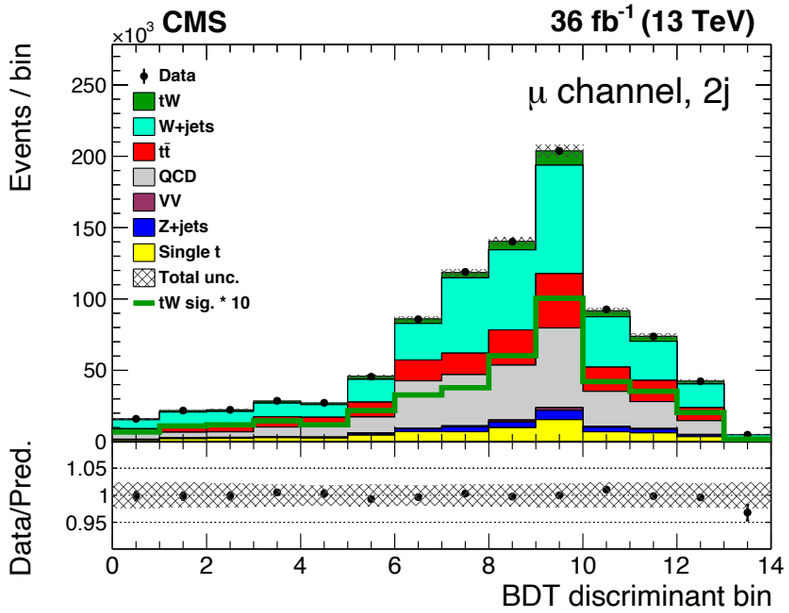
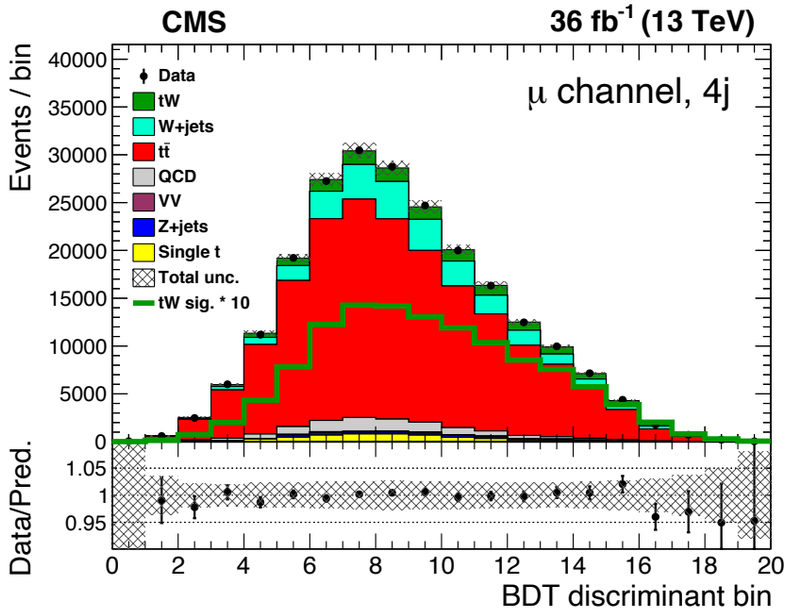
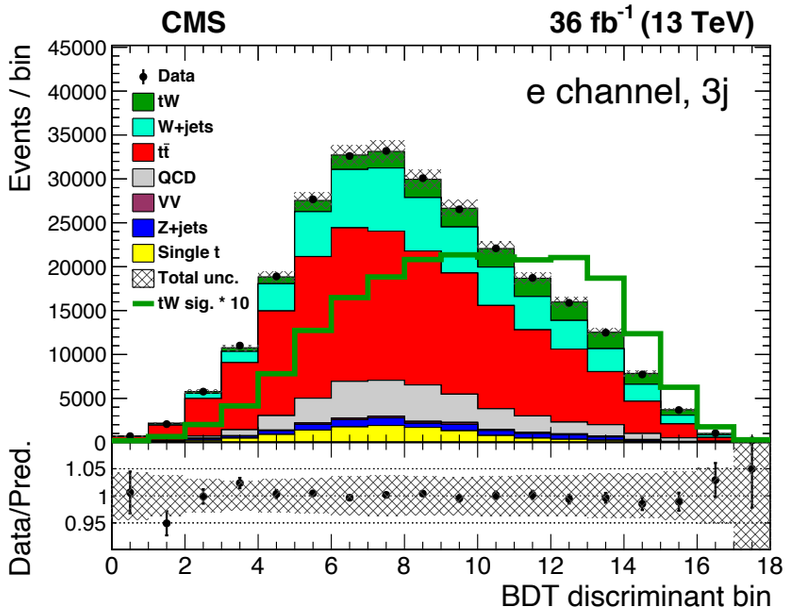


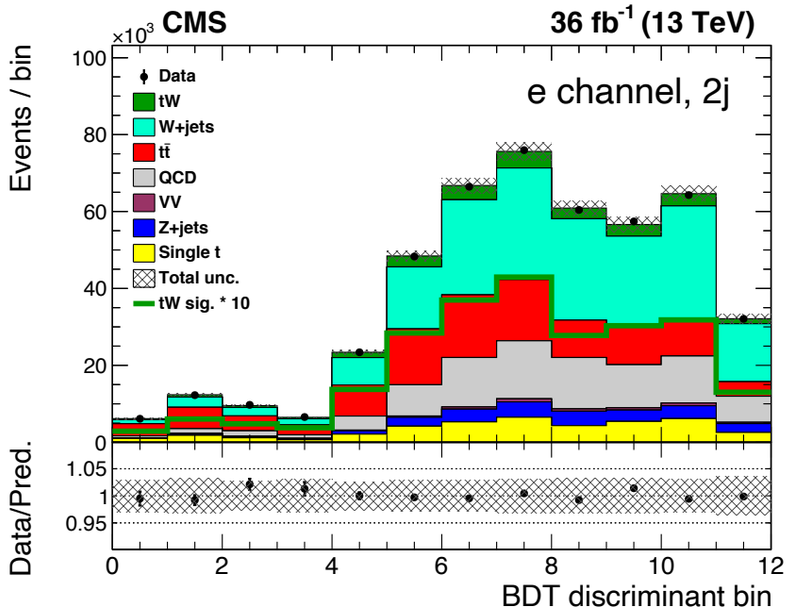
Observation of tW in single-lepton channel

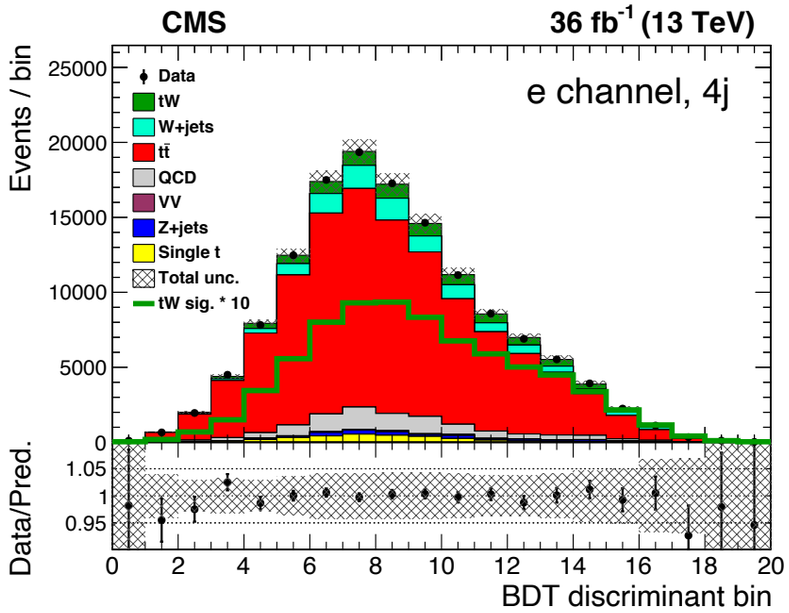












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Observation of tW in single-lepton channel

Sample	Muon channel		
	3j	2j	4j
tW	26083 ± 62	29814 ± 66	10612 ± 40
$t\bar{t}$	274100 ± 360	198120 ± 300	186200 ± 300
W+jets	79500 ± 1200	319800 ± 3200	18000 ± 480
QCD multijet	66830 ± 360	277610 ± 940	7700 ± 110
Single t	15786 ± 55	55250 ± 100	4124 ± 28
Z+jets	7290 ± 500	26950 ± 960	2080 ± 240
VV	2860 ± 160	7480 ± 250	754 ± 83
Total prediction	472500 ± 2700	915000 ± 5800	229400 ± 1300
Data	472540	923880	223720

Sample	Electron channel		
	3j	2j	4j
tW	15726 ± 35	17479 ± 36	6596 ± 23
$t\bar{t}$	156050 ± 200	109980 ± 160	108410 ± 160
W+jets	50230 ± 670	192400 ± 1800	12090 ± 310
QCD multijet	21120 ± 410	87880 ± 680	2370 ± 79
Single t	8937 ± 30	30335 ± 54	2379 ± 15
Z+jets	6960 ± 300	24170 ± 590	1840 ± 140
VV	1635 ± 84	4050 ± 130	463 ± 44
Total prediction	260700 ± 1700	466300 ± 3500	134000 ± 780
Data	270330	462940	136190

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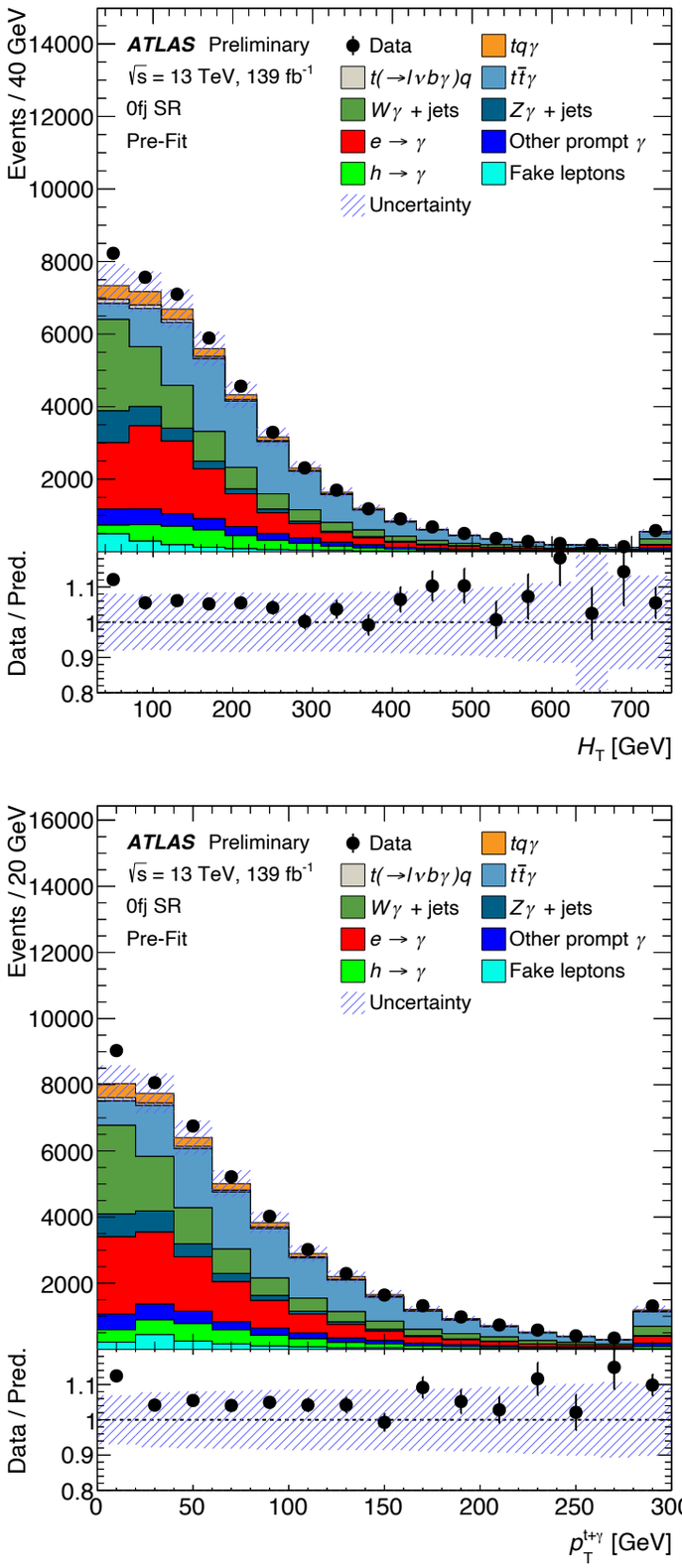
Observation of single top + γ production

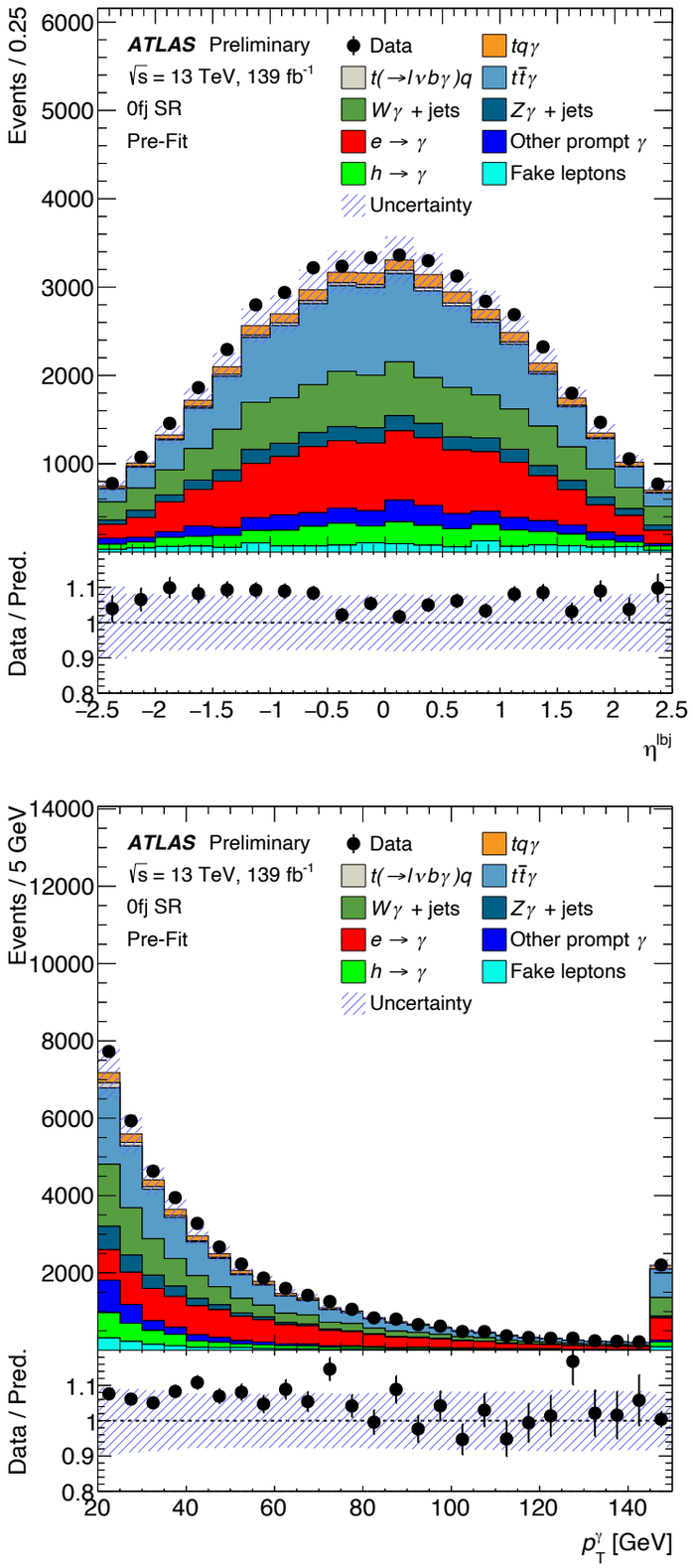
[ATLAS-CONF-2022-013]

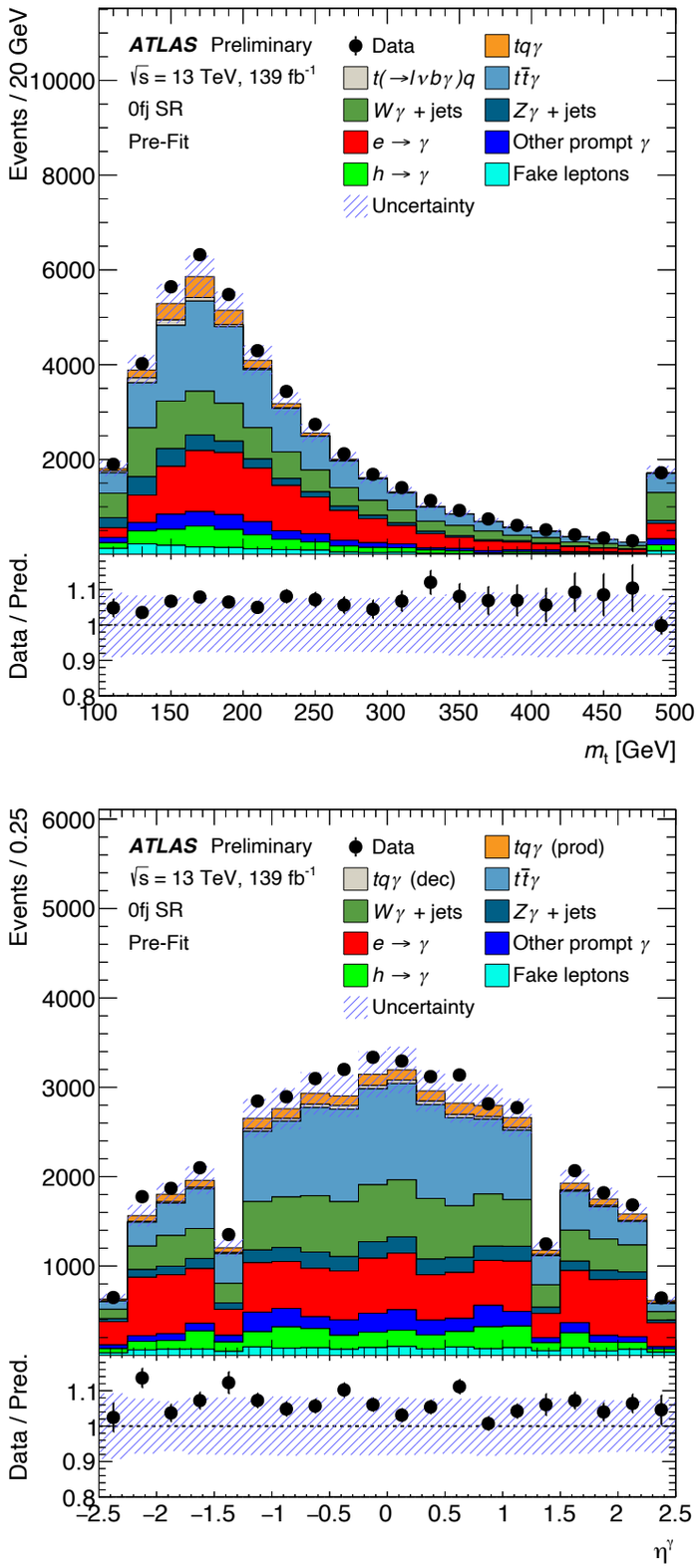
Observation of single top + γ production

ATLAS-CONF-2022-013

New





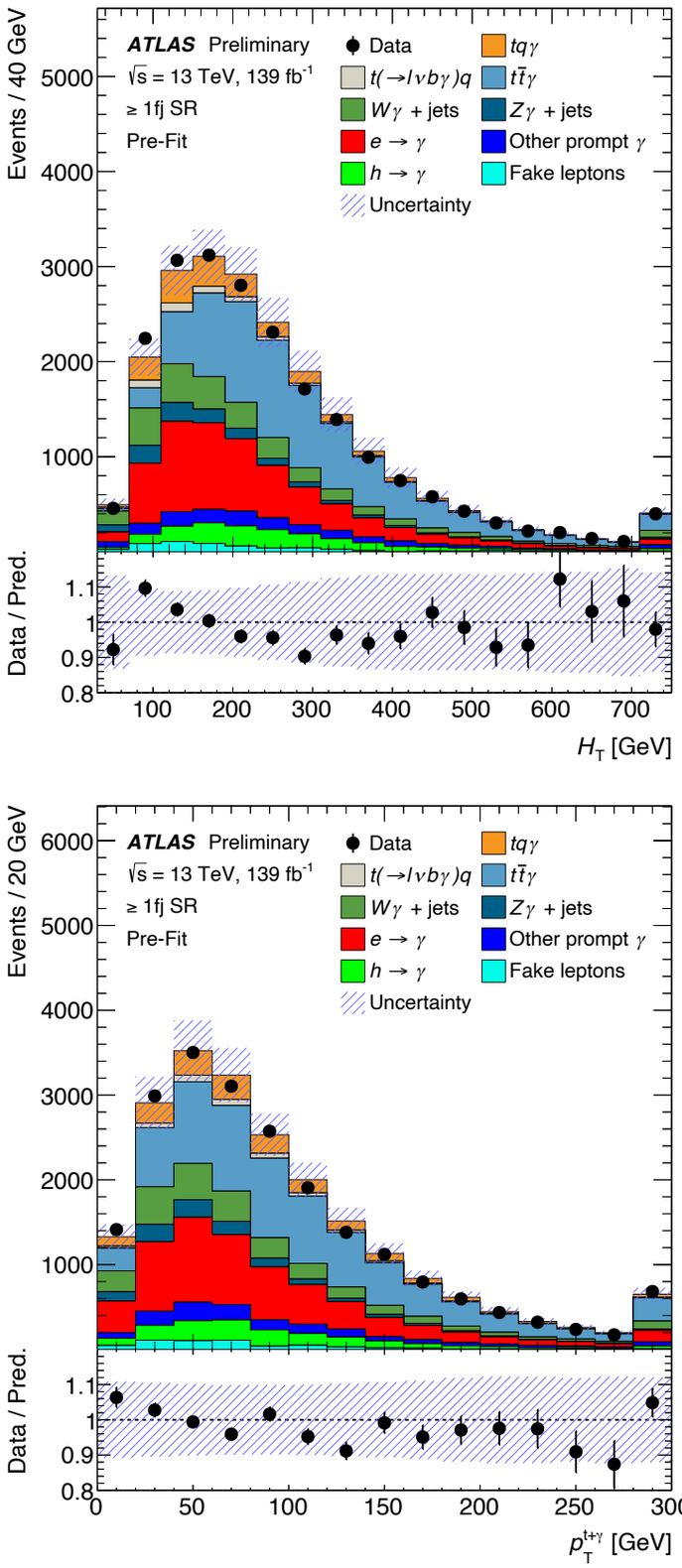


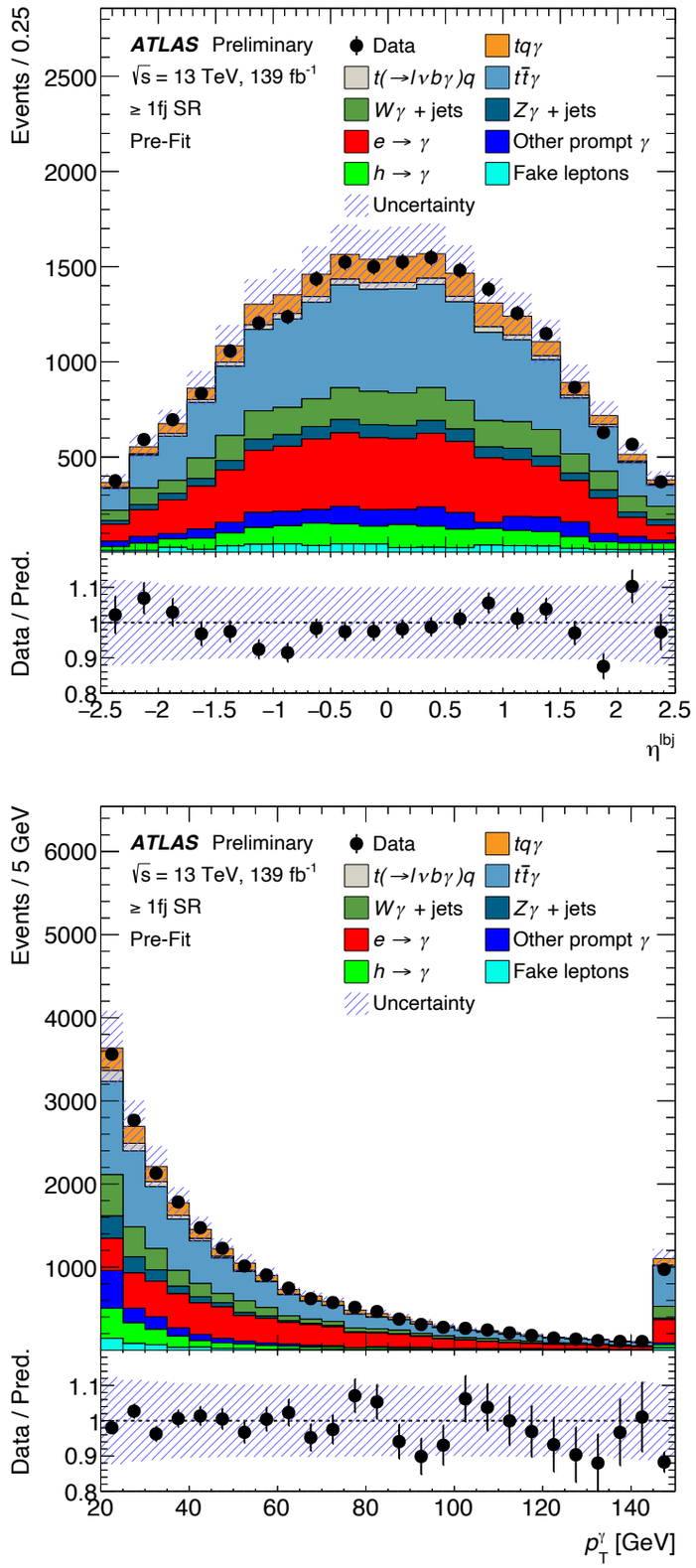
0fj SR

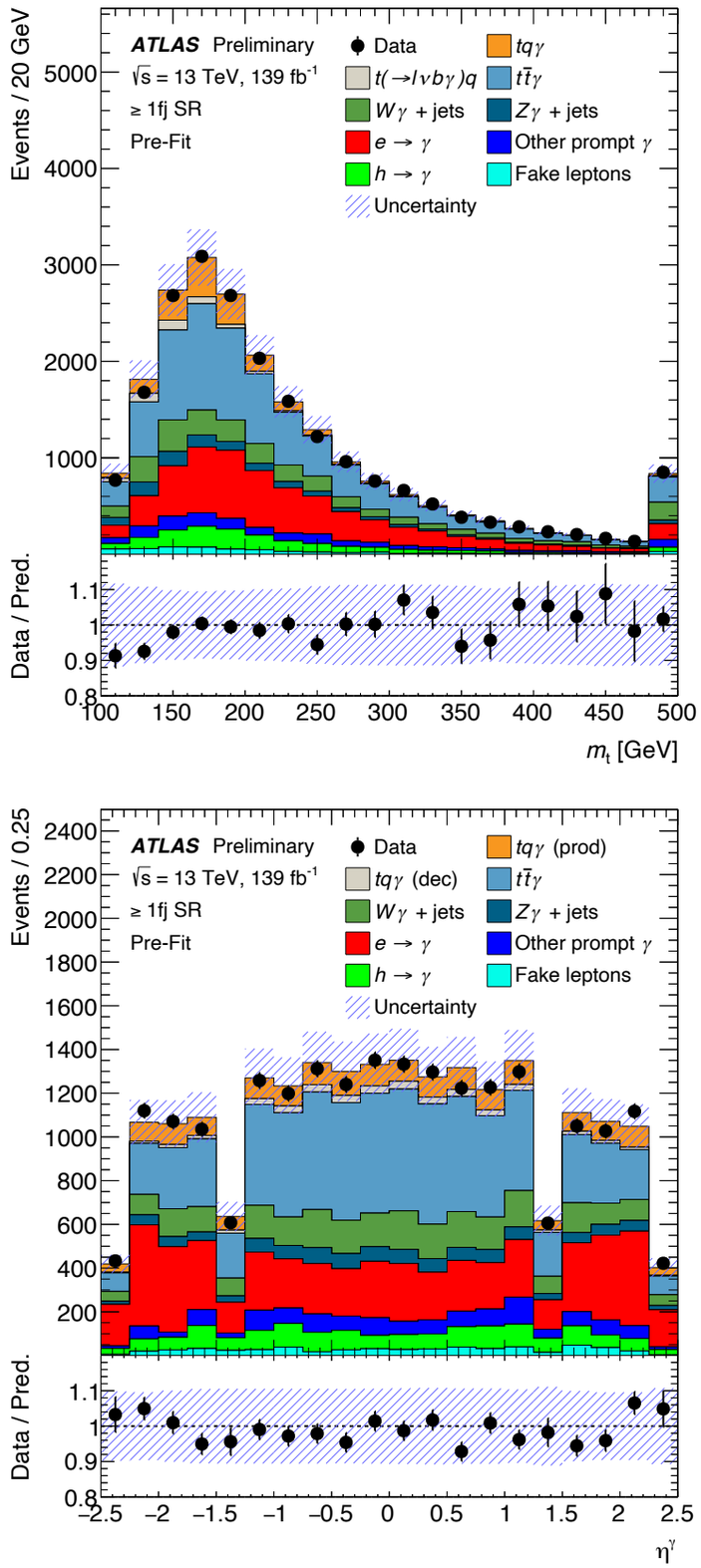
Observation of single top + γ production

ATLAS-CONF-2022-013

New







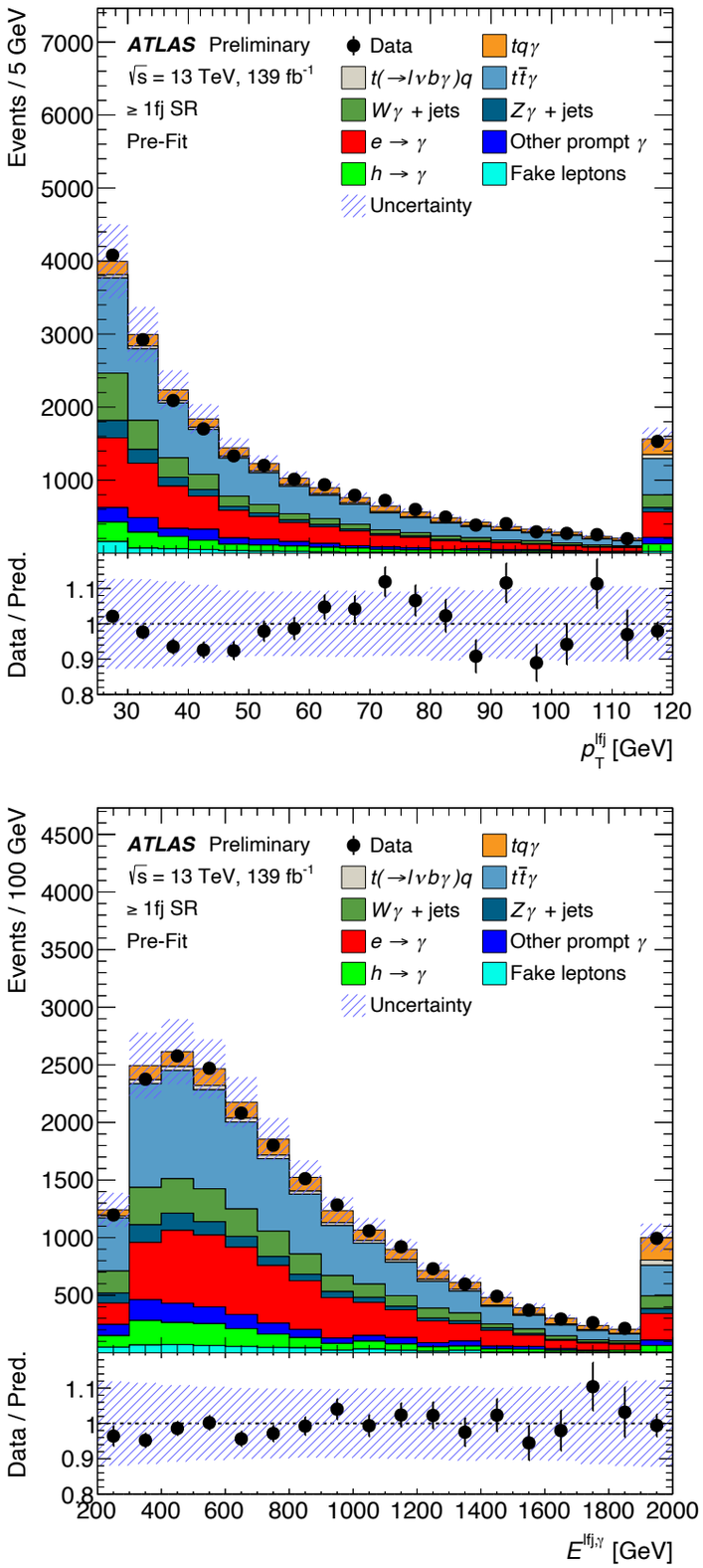
≥ 1fj SR

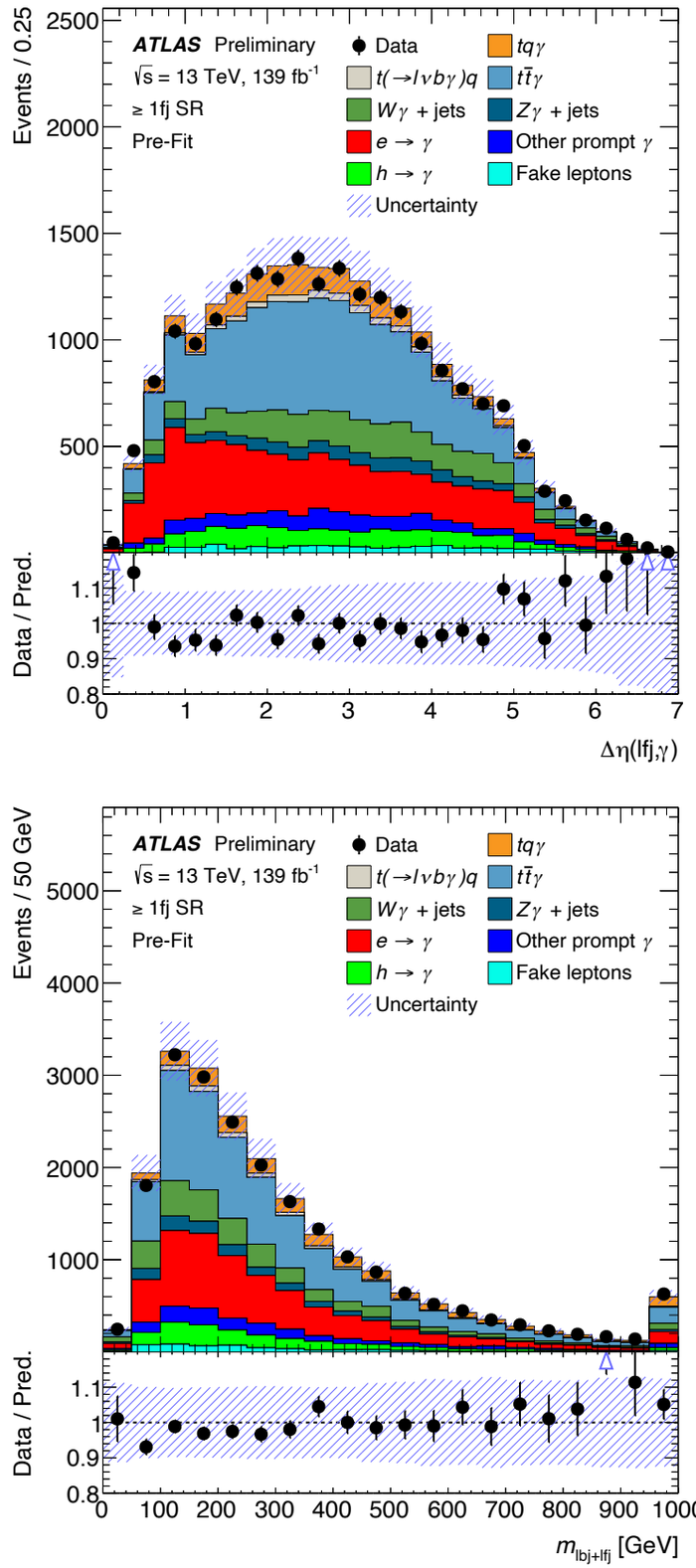
Observation of single top + γ production

ATLAS-CONF-2022-013

New

≥ 1fj SR





Measurement of m_t in single-top events

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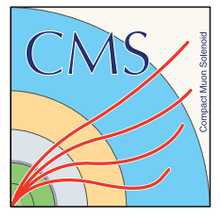
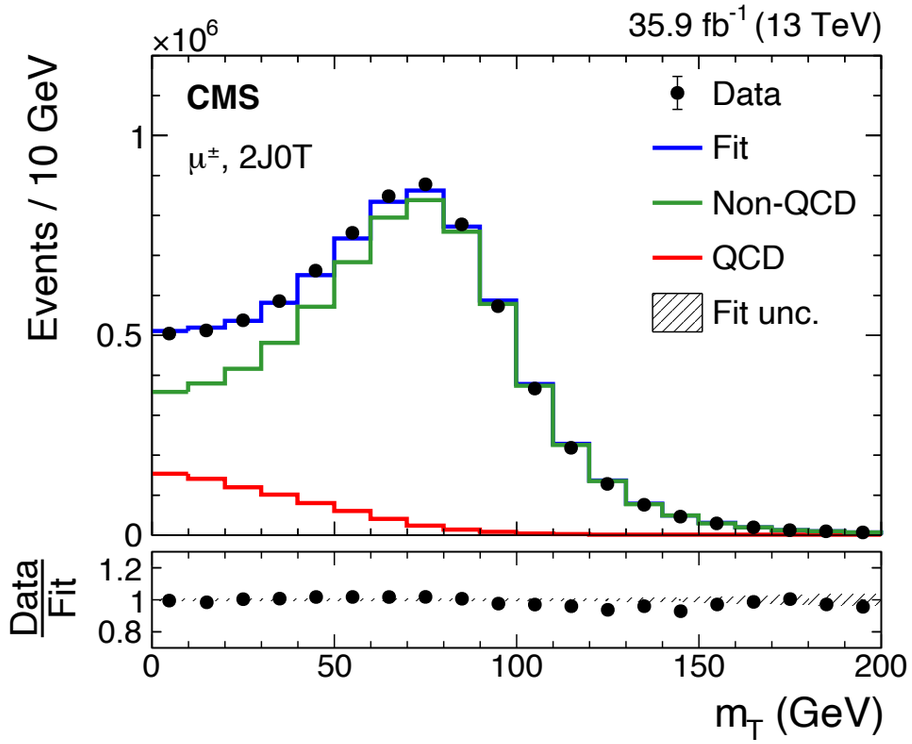
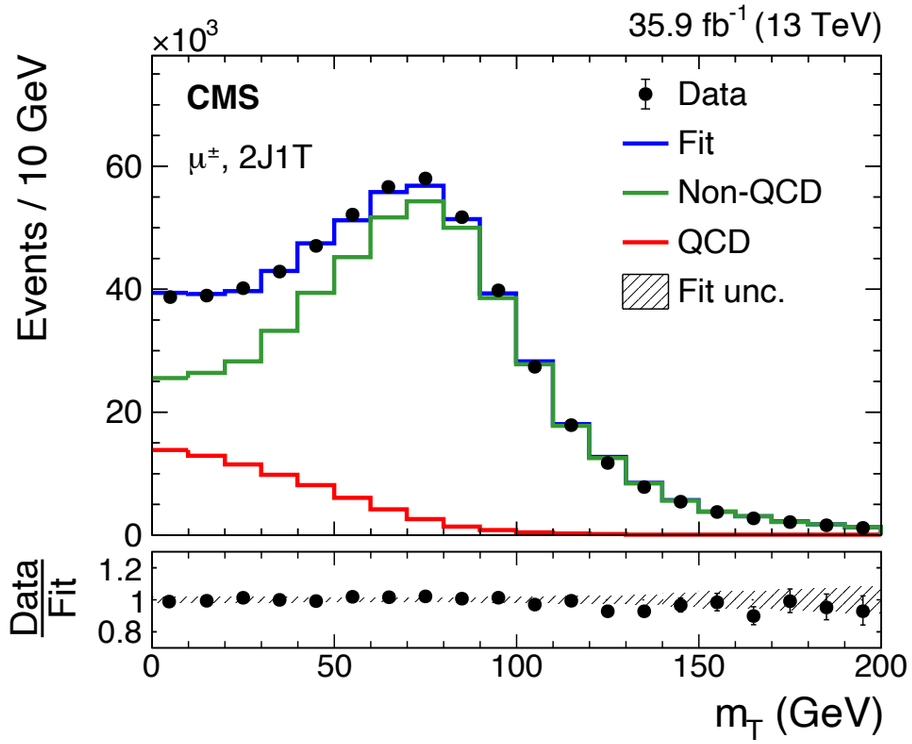
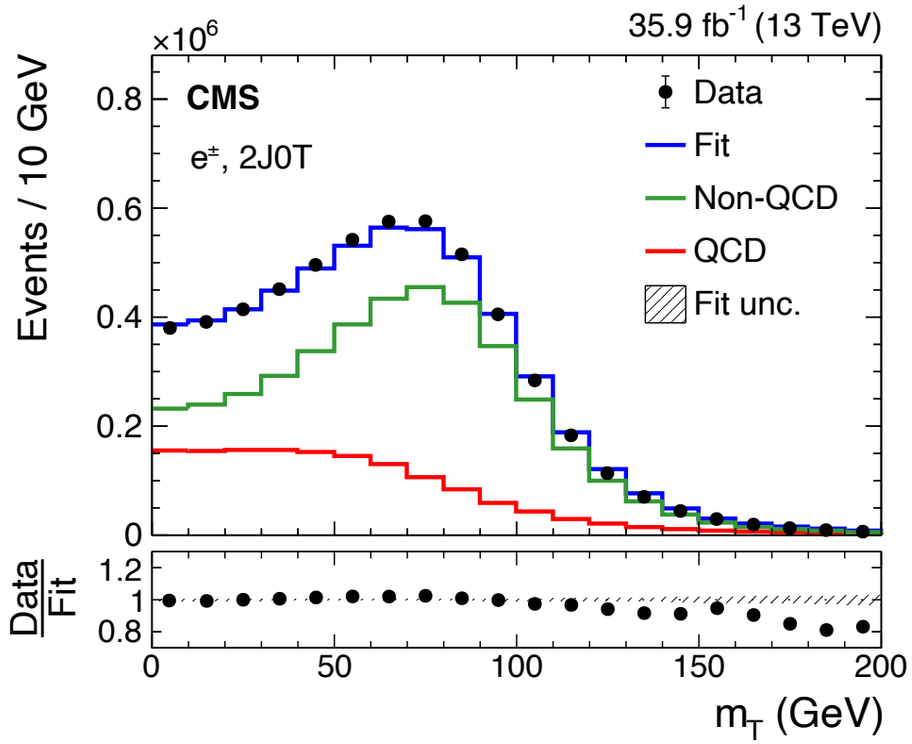
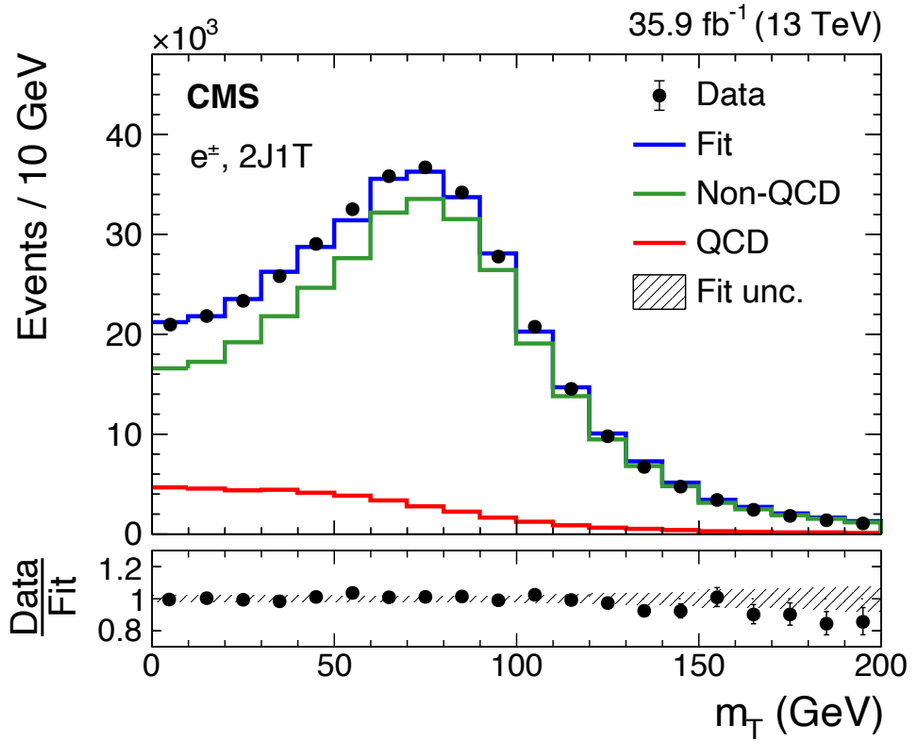


Measurement of m_t in single-top events

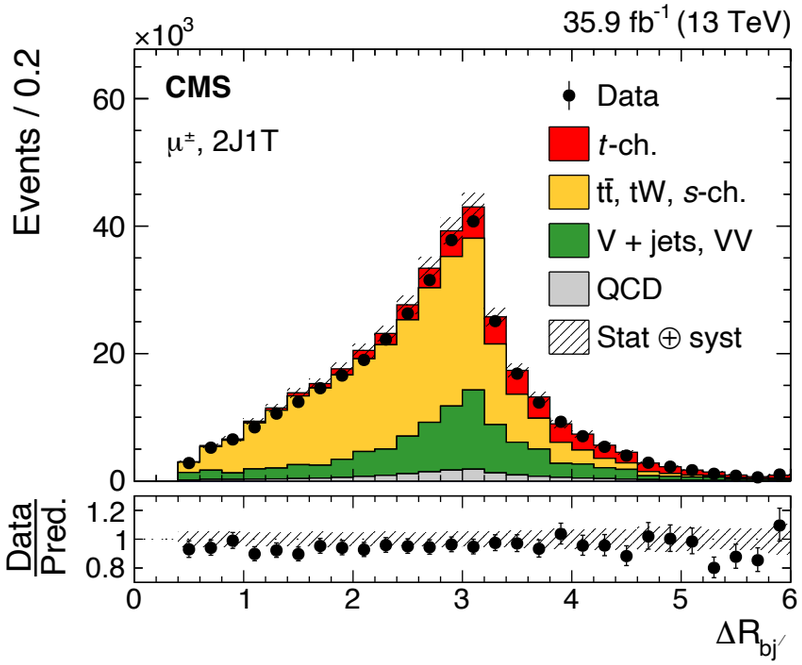


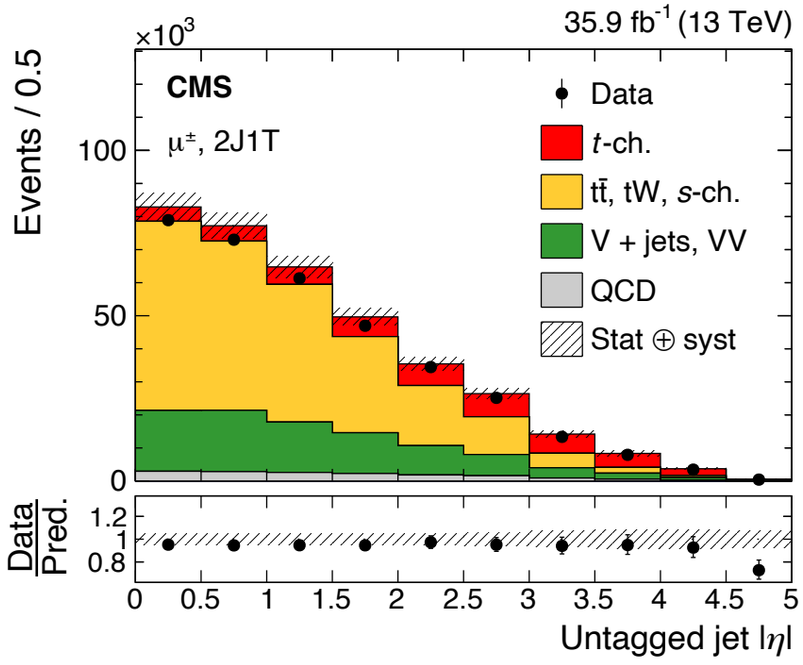


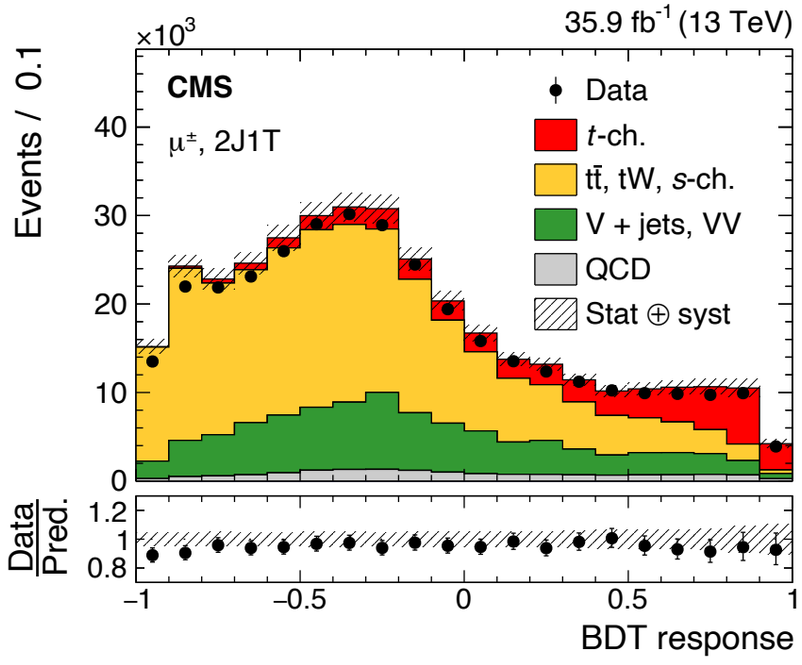


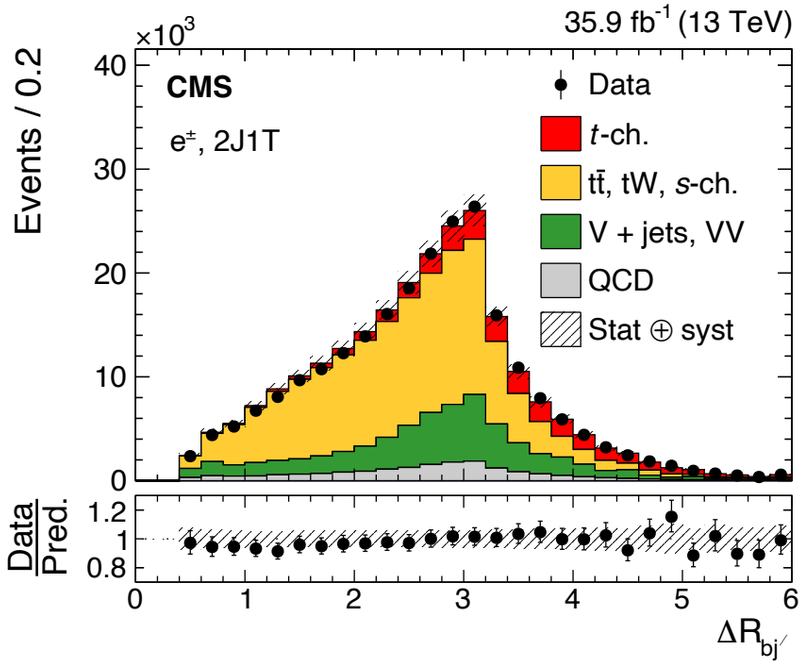


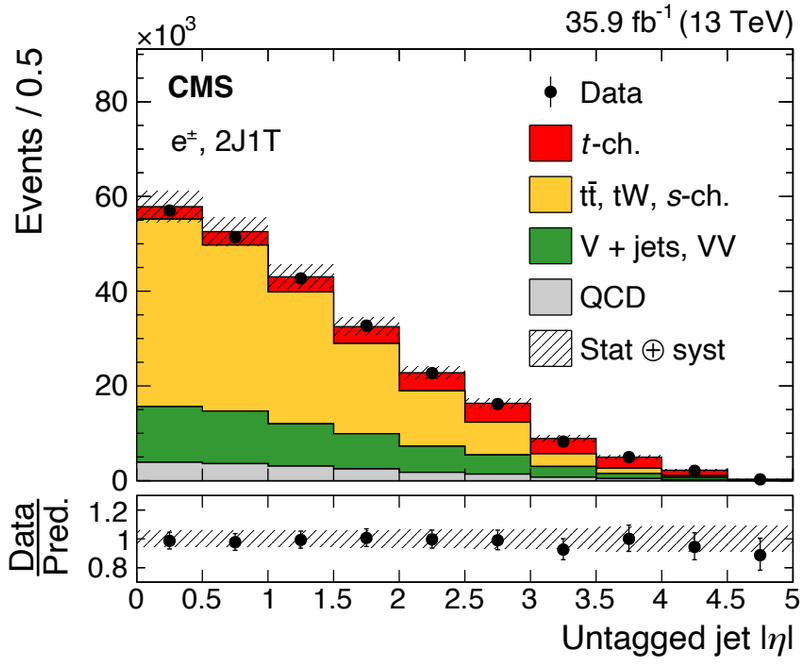
Measurement of m_t in single-top events

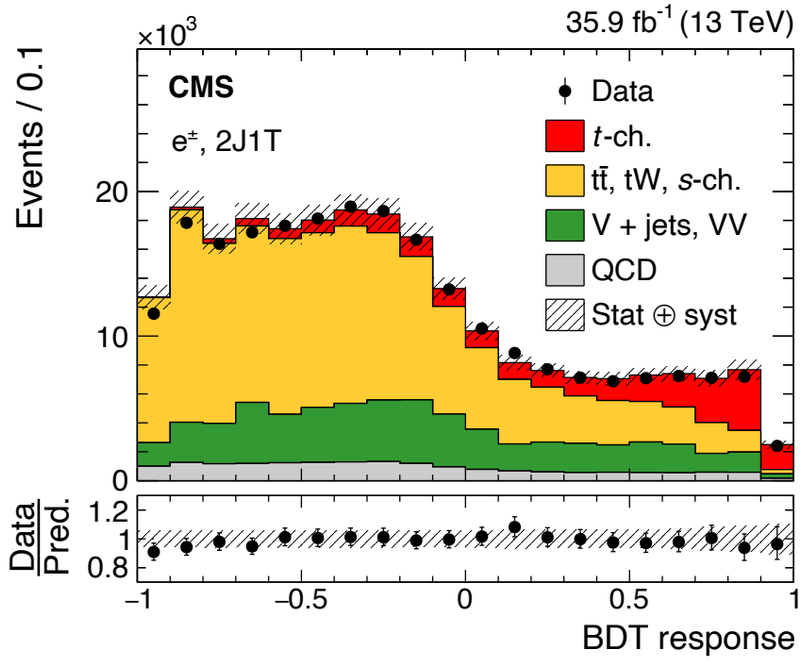




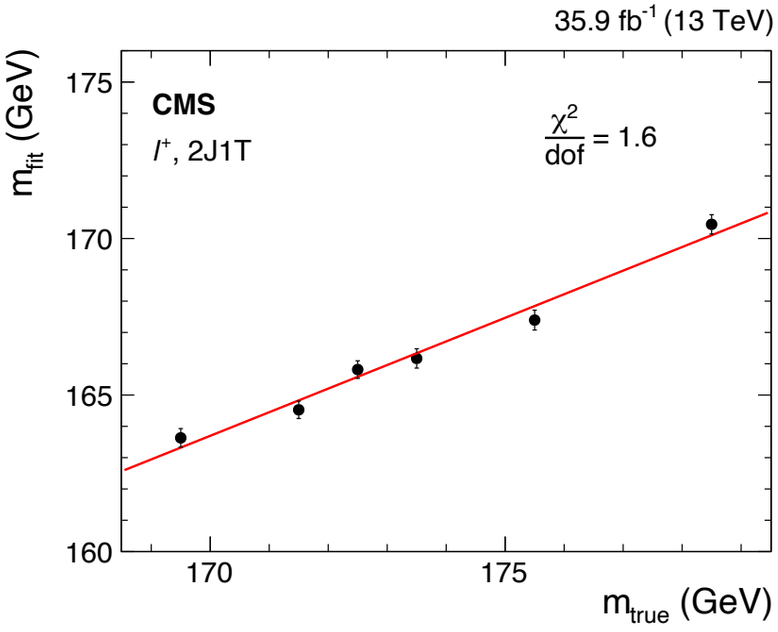


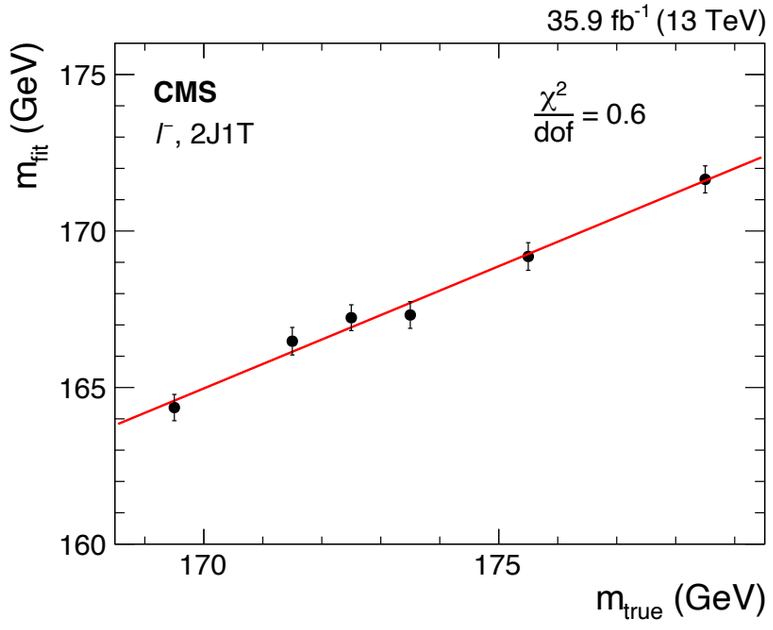


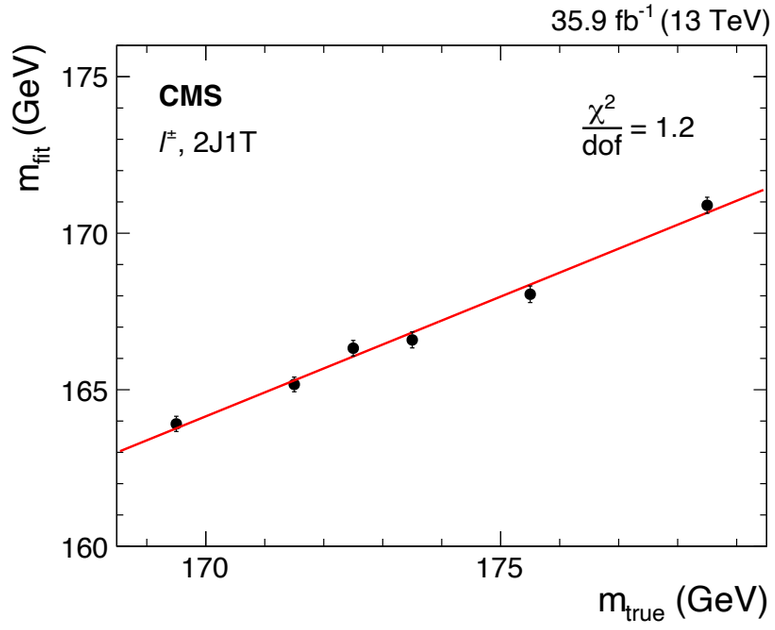


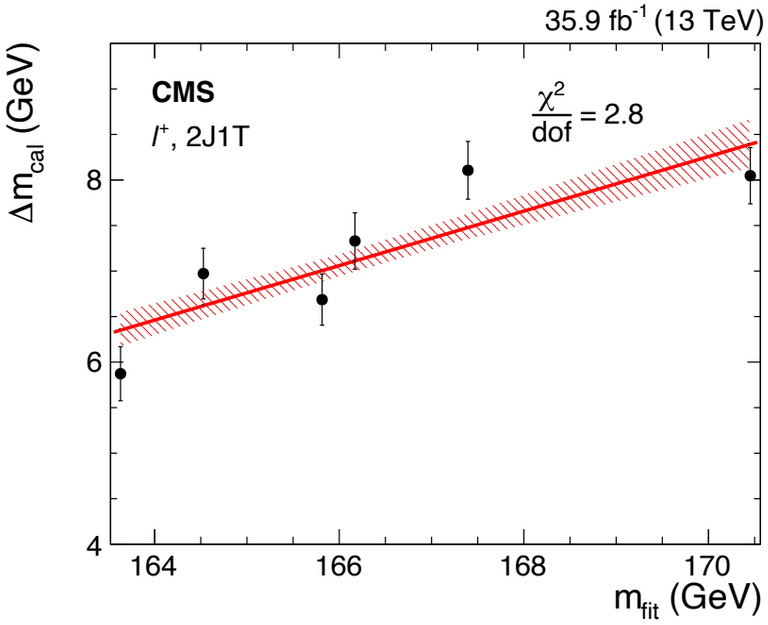


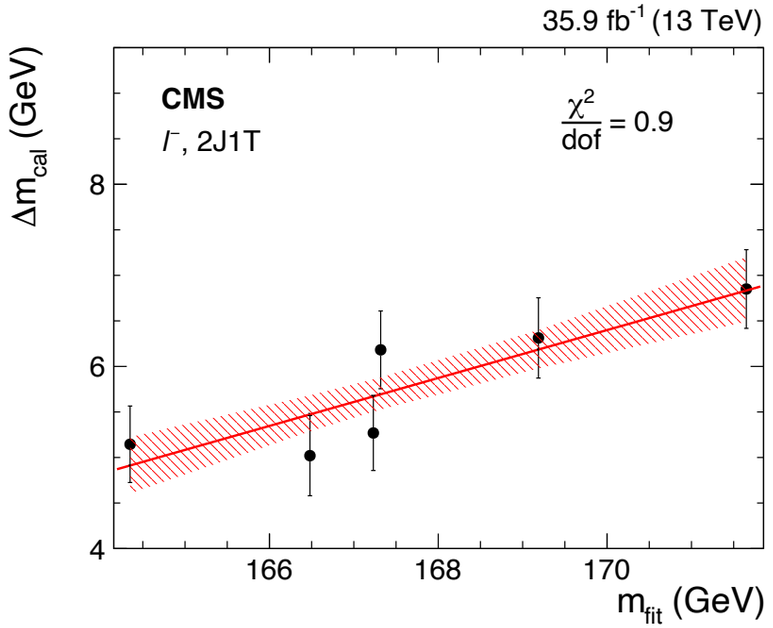
Measurement of m_t in single-top events

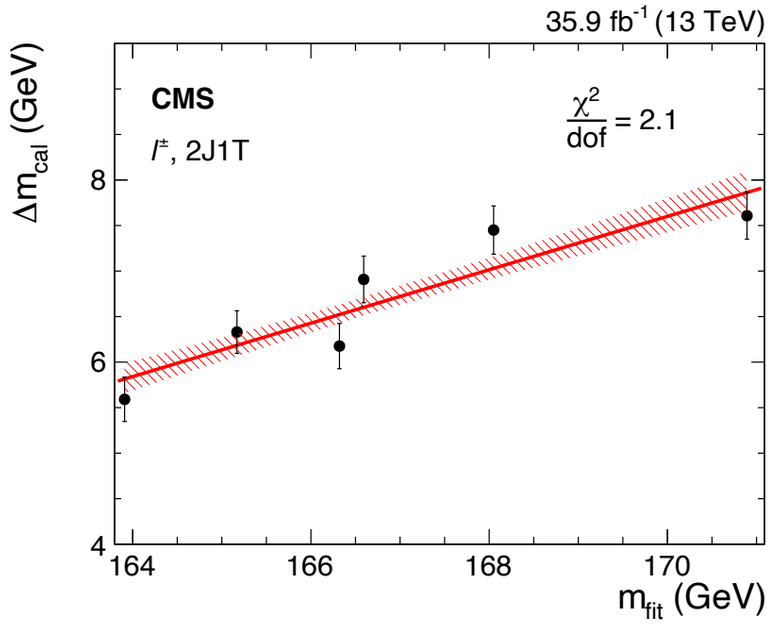












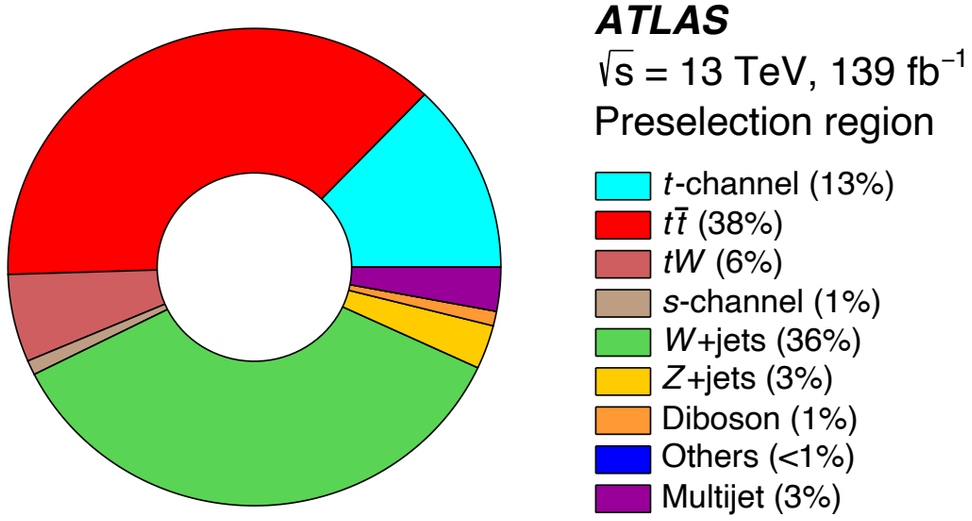
Measurement of m_t in single-top events

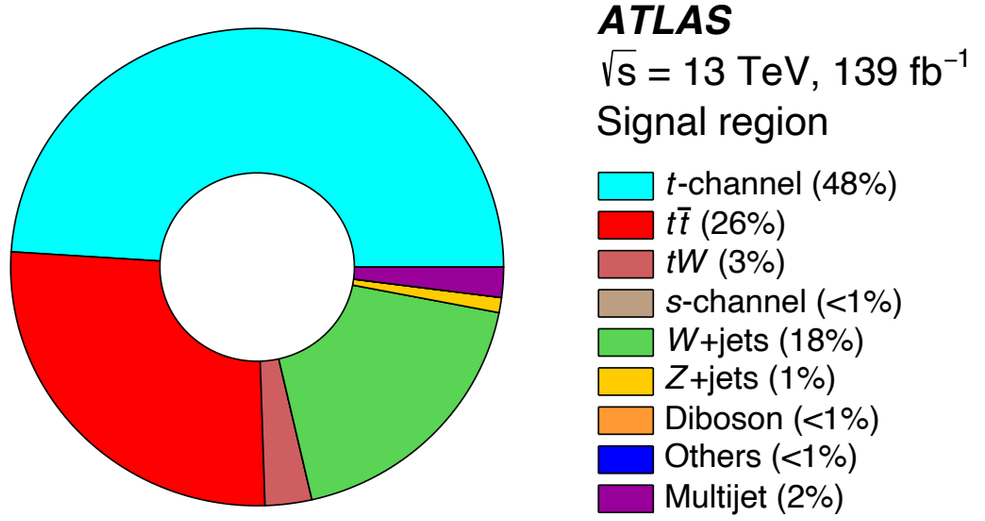
Variable	Rank Muon	Rank Electron	Description
$\Delta R_{\mathrm{bj'}}$	1	1	Angular separation in (η, ϕ) space between the b-tagged and untagged jets
Untagged jet $\lvert\eta\rvert$ ($\lvert\eta_{\mathrm{j'}}\rvert$)	2	2	Absolute pseudorapidity of the untagged jet
$m_{\mathrm{bj'}}$	3	3	Invariant mass of the system comprising the b-tagged and untagged jets
$\cos\theta^*$	4	4	Cosine of the angle between the lepton and untagged jet in the rest frame of the top quark
m_{T}	5	5	Transverse mass as defined in Eq. (**??**)
FW1	—	6	First-order Fox–Wolfram moment [**?** **?**] (electron final state)
$\lvert\Delta\eta_{l\mathrm{b}}\rvert$	6	7	Absolute pseudorapidity difference between the lepton and b-tagged jet
$p_{\mathrm{T}}^{\mathrm{b}} + p_{\mathrm{T}}^{\mathrm{j'}}$	7	8	Scalar sum of the p_{T} of the b-tagged and untagged jets
$\lvert\eta_l\rvert$	8	—	Absolute pseudorapidity of the lepton (muon final state)

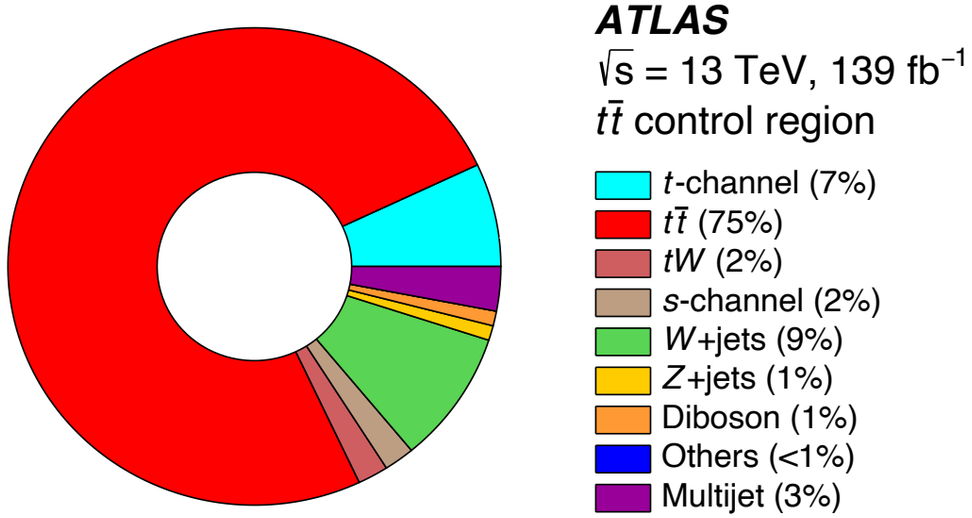
Top quark polarisation

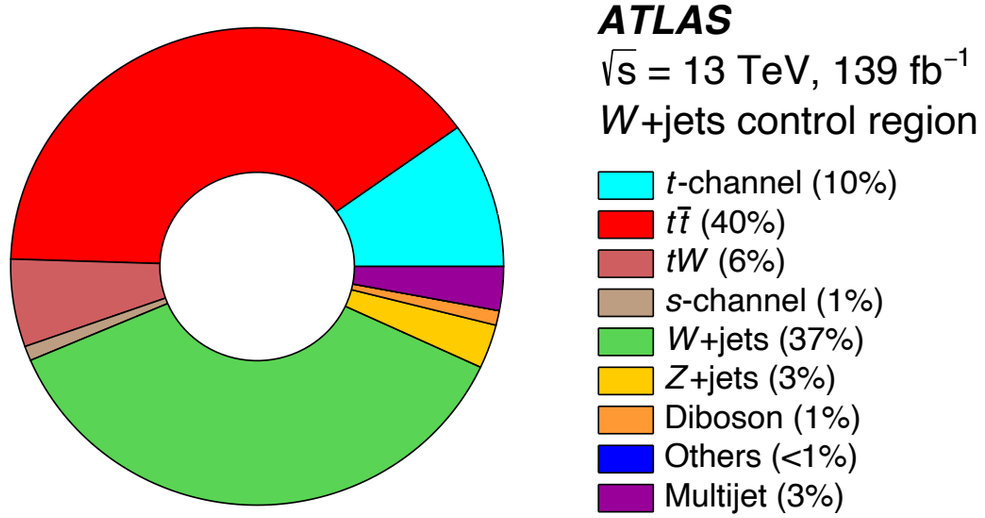
arXiv:2202.11382 [hep-ex]

Top quark polarisation









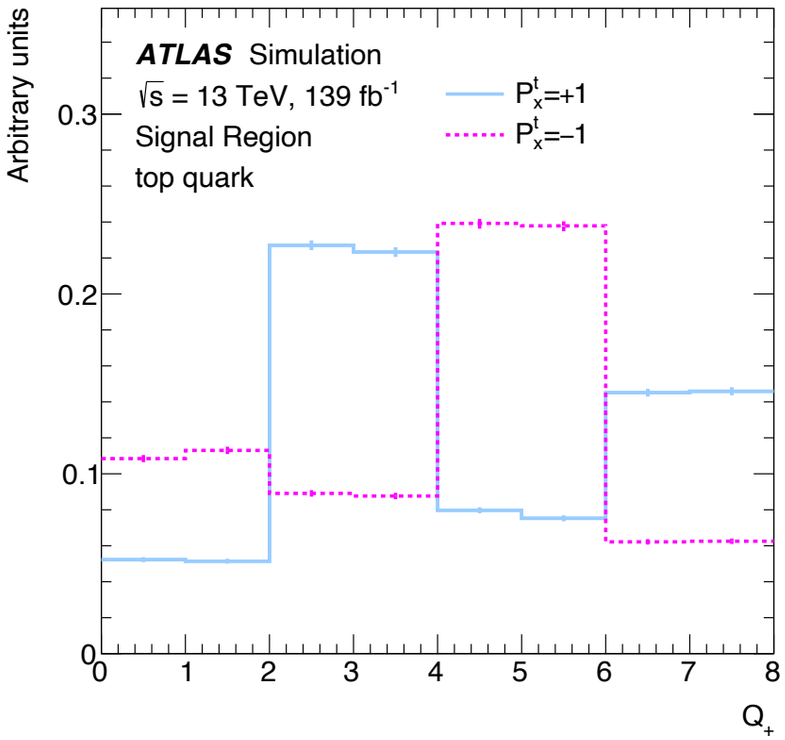
Top quark polarisation

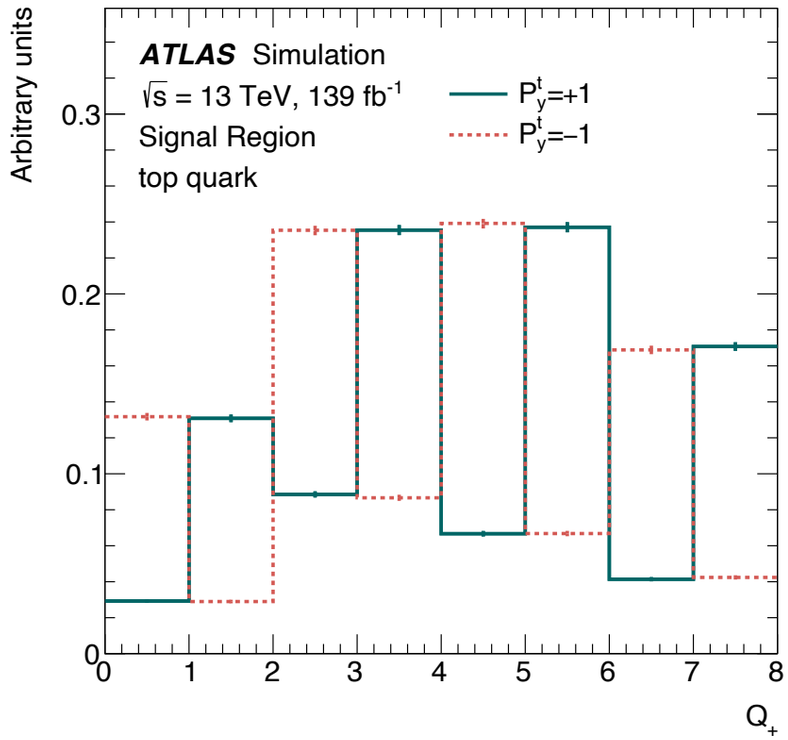
Common event selection criteria
Exactly one electron or muon
Veto secondary low-p_{T} charged loose leptons
Exactly two jets
$E_{\mathrm{T}}^{\mathrm{miss}} > 35\,\mathrm{GeV}$
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) > 60\,\mathrm{GeV}$
$p_{\mathrm{T}}(\ell) > 50\left(1 - \frac{\pi - \lvert\Delta\phi(p_{\mathrm{T}}(j_1), p_{\mathrm{T}}(\ell))\rvert}{\pi - 1}\right)\,\mathrm{GeV}$

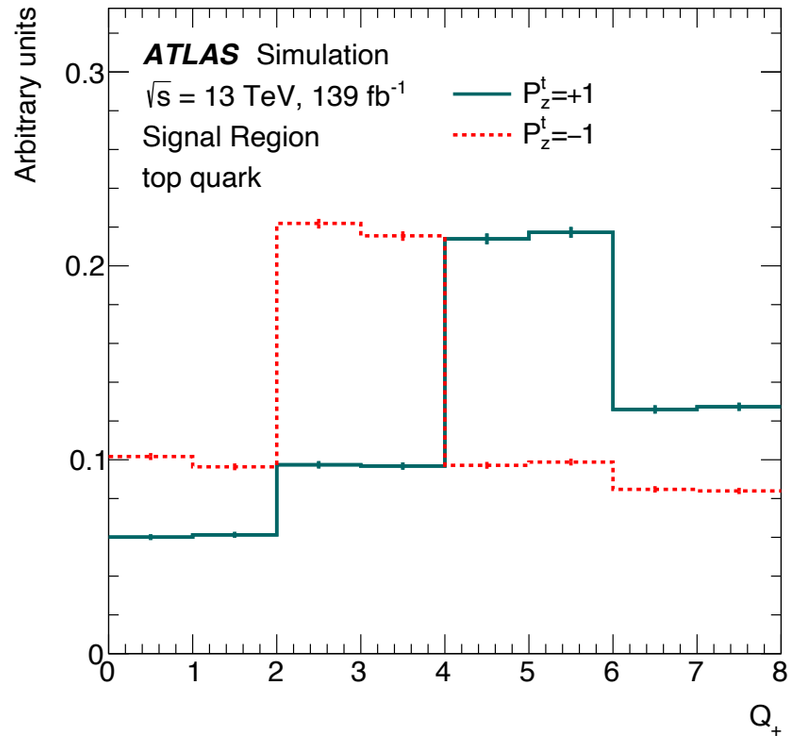
Preselection region	Signal region	$t\bar{t}$ control region	W+jets control region
Exactly one b-tagged jet	Exactly one b-tagged jet $m_{\ell b} < 153$ GeV $m_{j\ell\nu b} > 320$ GeV Trapezoidal requirement $H_{\mathrm{T}} > 190$ GeV	Exactly two b-tagged jet	Exactly one b-tagged jet $m_{\ell b} > 153$ GeV $m_{j\ell\nu b} < 320$ GeV Veto trapezoidal requirement $H_{\mathrm{T}} < 190$ GeV

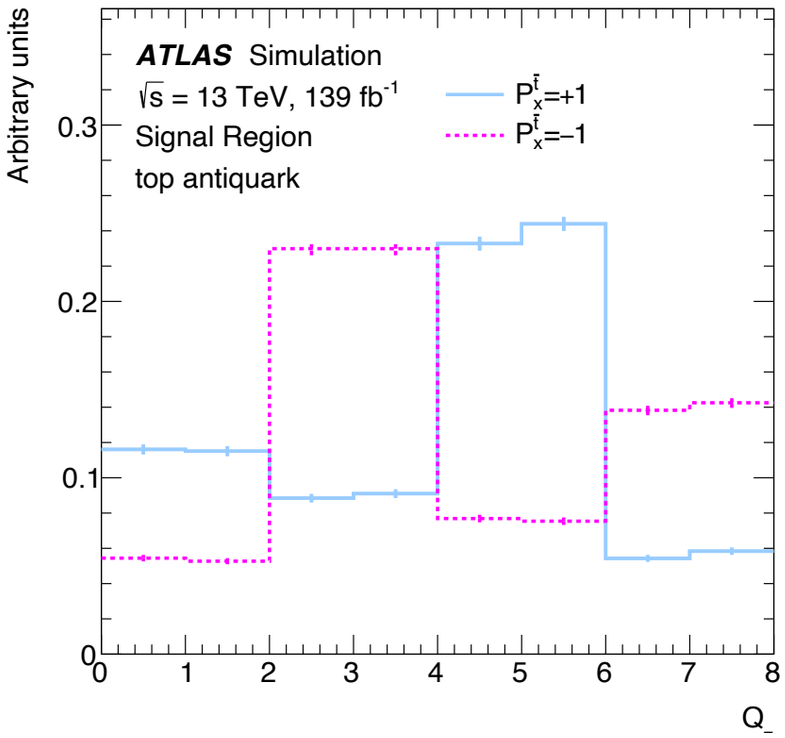
Process	Preselection region	Signal region	$t\bar{t}$ control region	W+jets control region
t-channel	219 000 ± 11 000	70 600 ± 3500	13 480 ± 680	148 200 ± 7400
$t\bar{t}$, tW, s-channel	736 000 ± 39 000	43 200 ± 2400	147 800 ± 8400	693 000 ± 37 000
W+jets	590 000 ± 200 000	26 200 ± 8900	16 100 ± 5500	560 000 ± 190 000
Z+jets, diboson	52 900 ± 5100	2120 ± 350	2620 ± 360	50 800 ± 4900
Others	494 ± 38	30 ± 4	79 ± 6	464 ± 36
Multijet	52 000 ± 10 000	3500 ± 640	5500 ± 1800	48 500 ± 9400
Total expected	1 650 000 ± 210 000	145 600 ± 9900	186 000 ± 10 000	1 510 000 ± 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

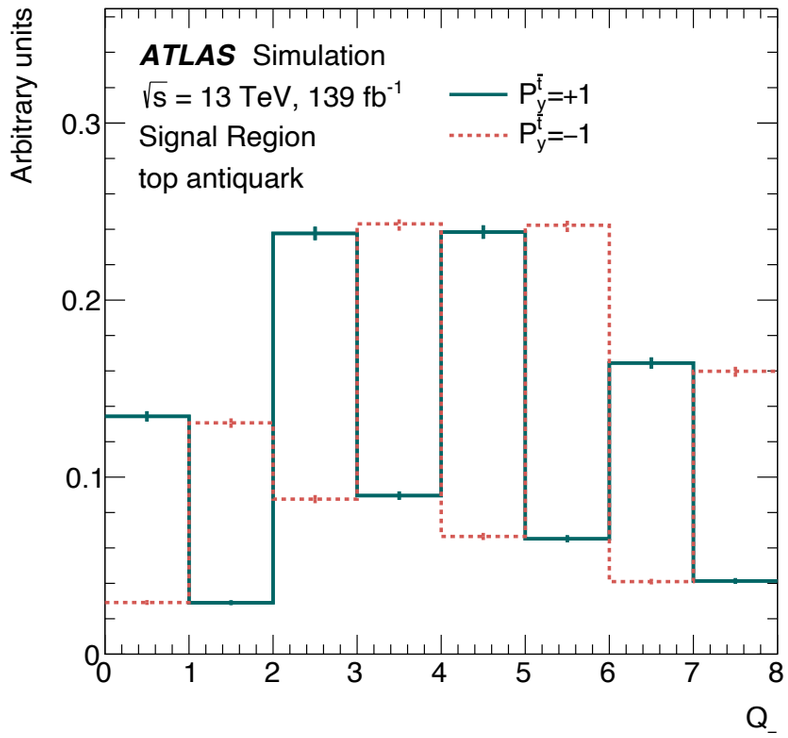
Top quark polarisation

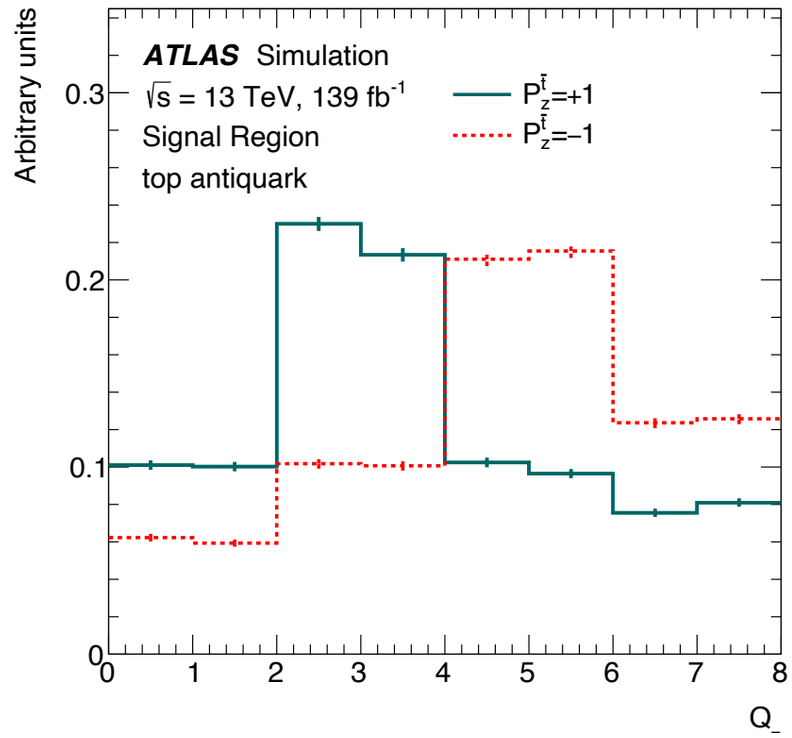






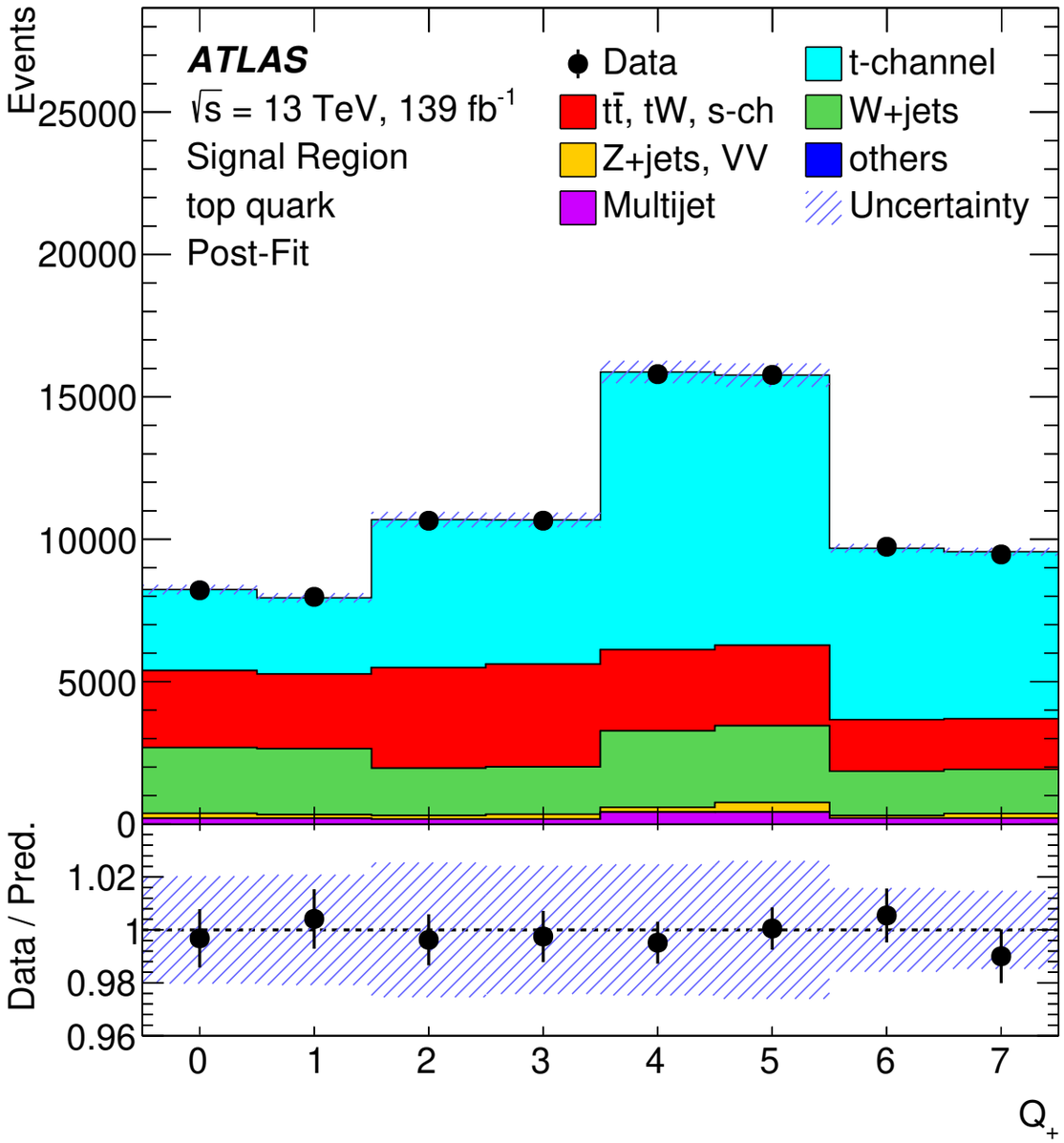


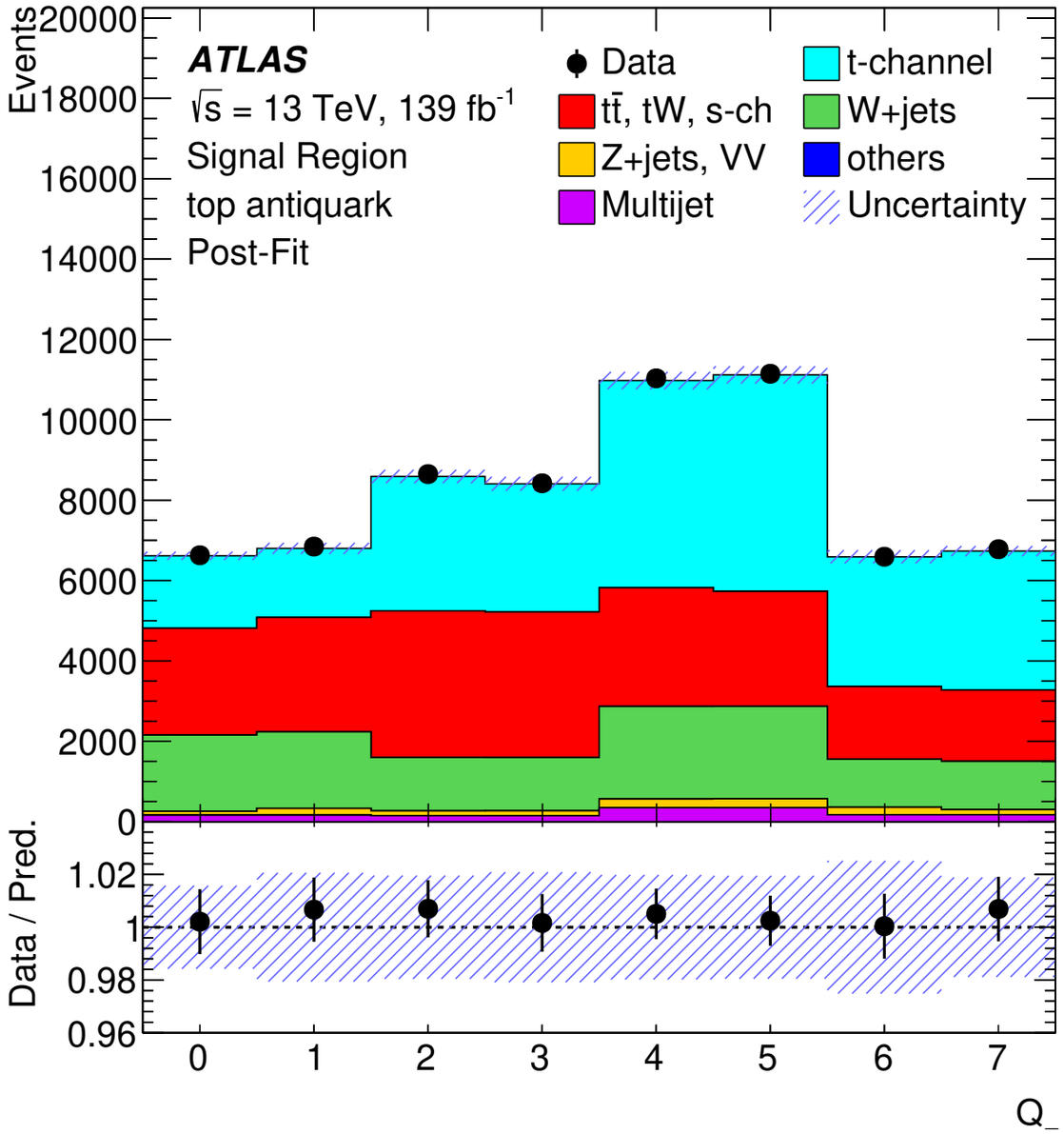




arXiv:2202.11382 [hep-ex]

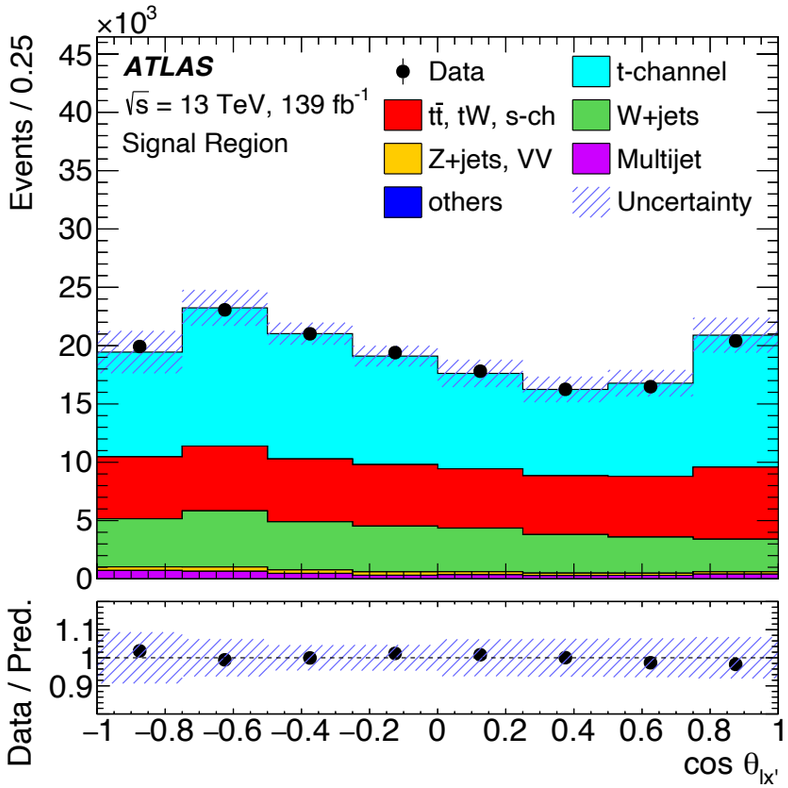
Top quark polarisation

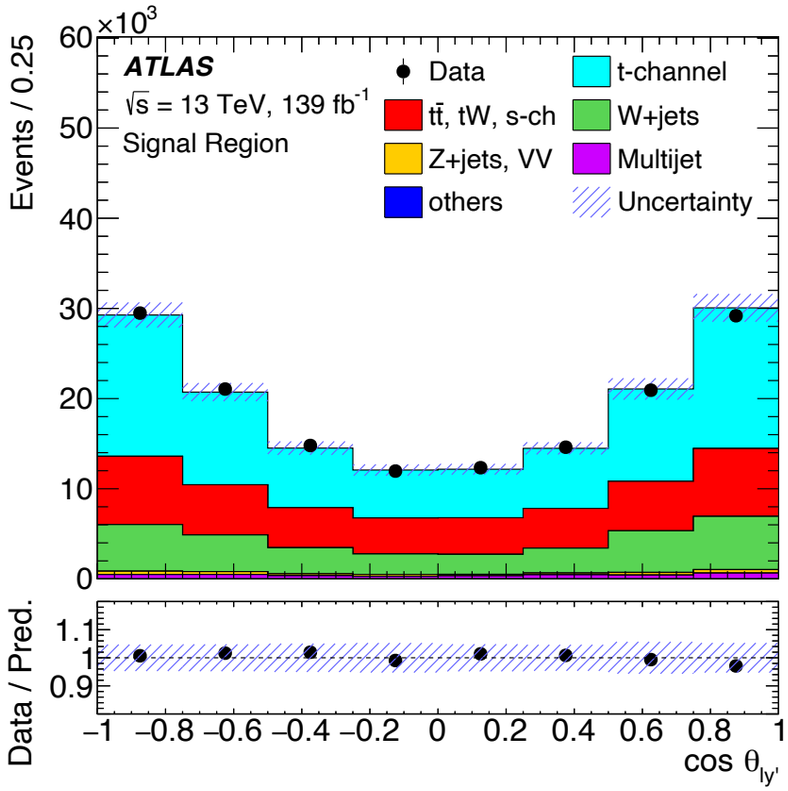


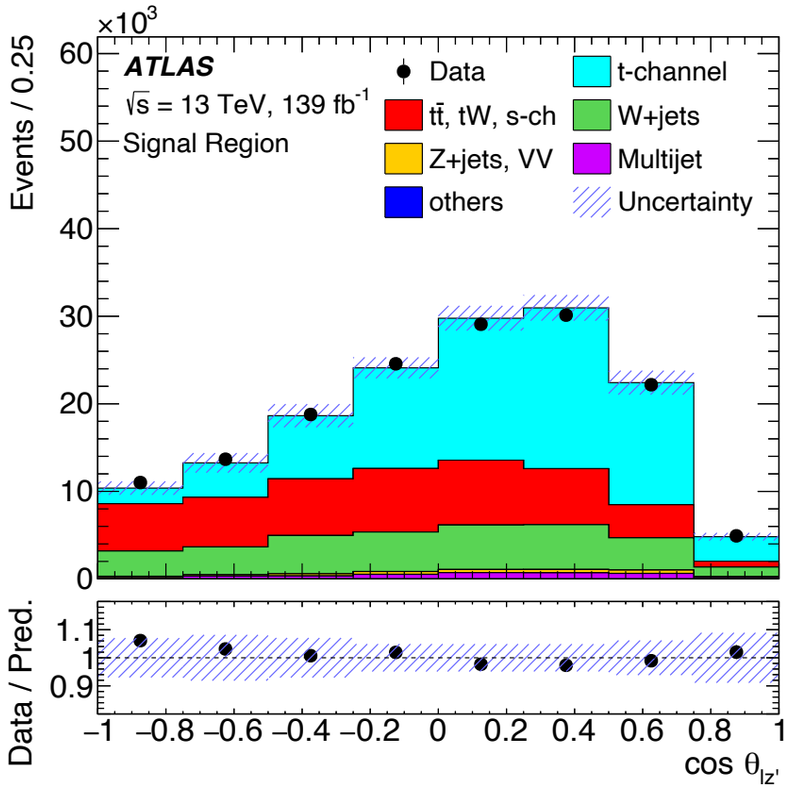


arXiv:2202.11382 [hep-ex]

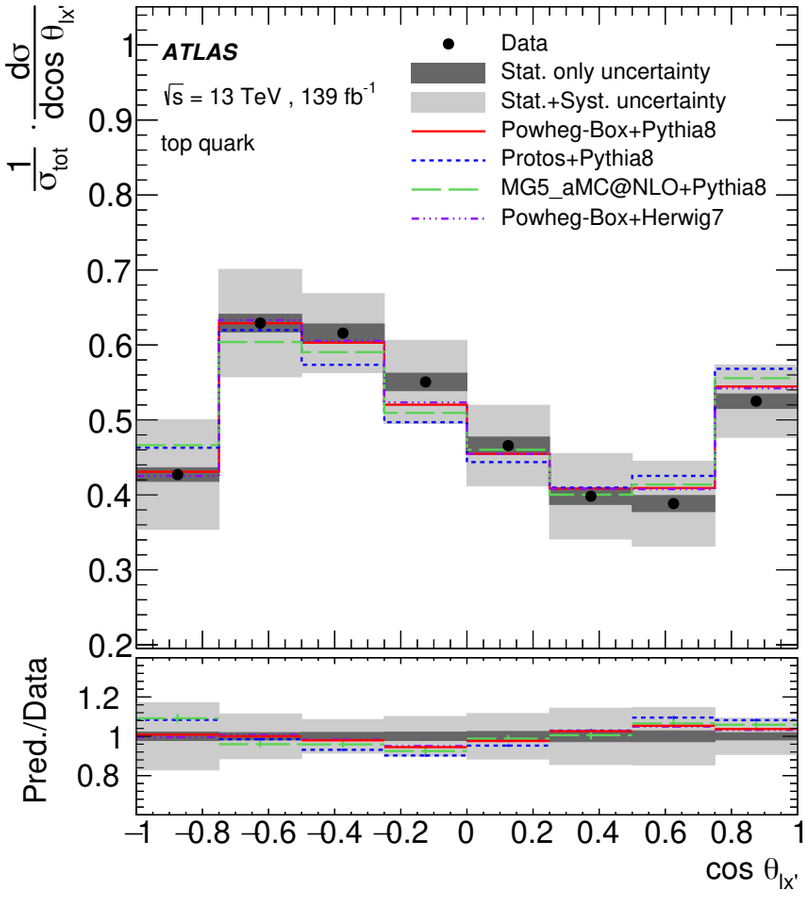
Top quark polarisation

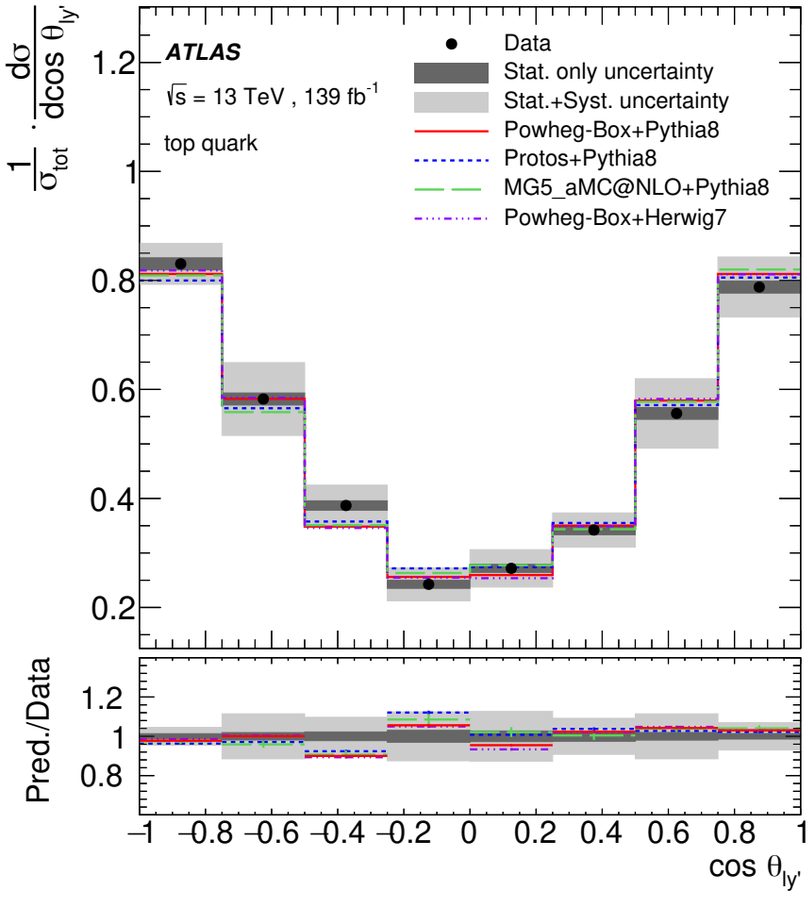


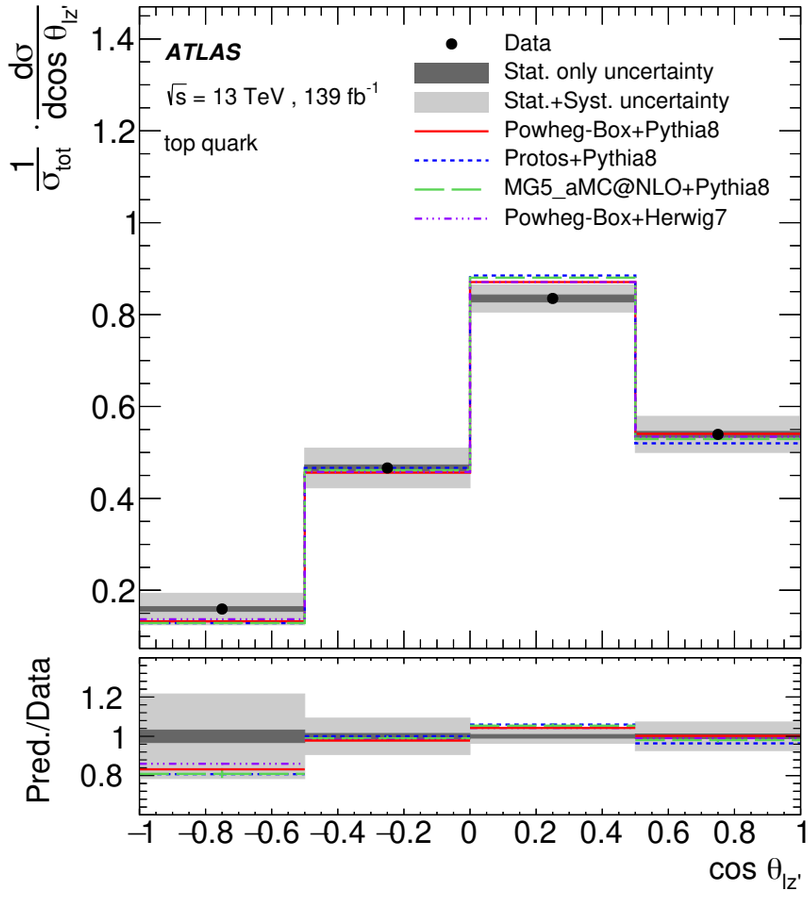




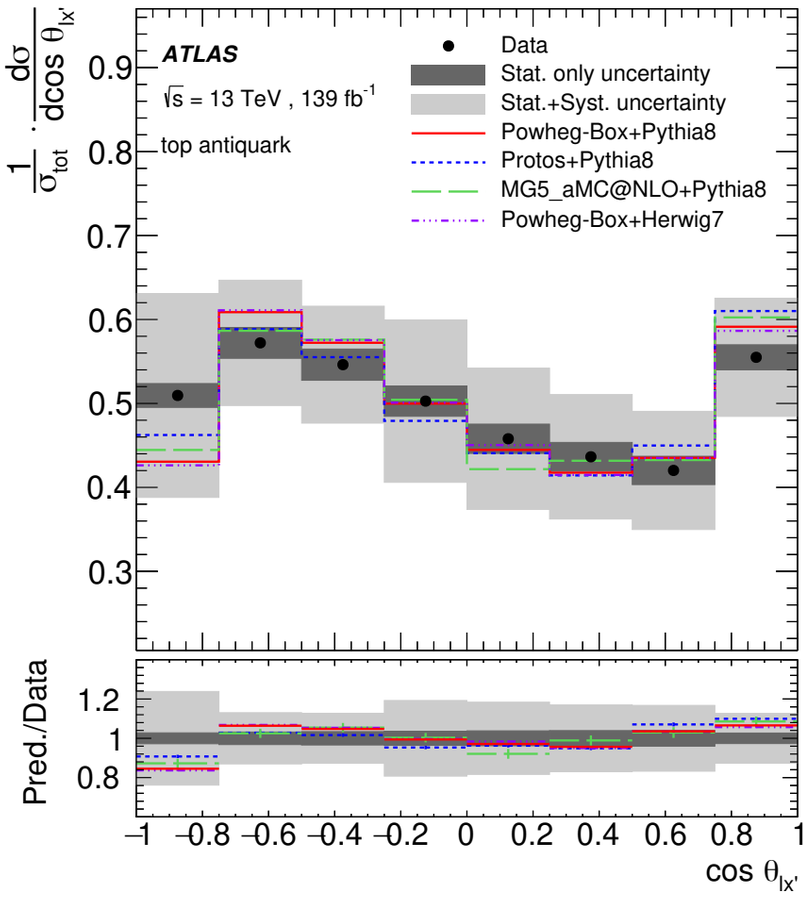
Top quark polarisation

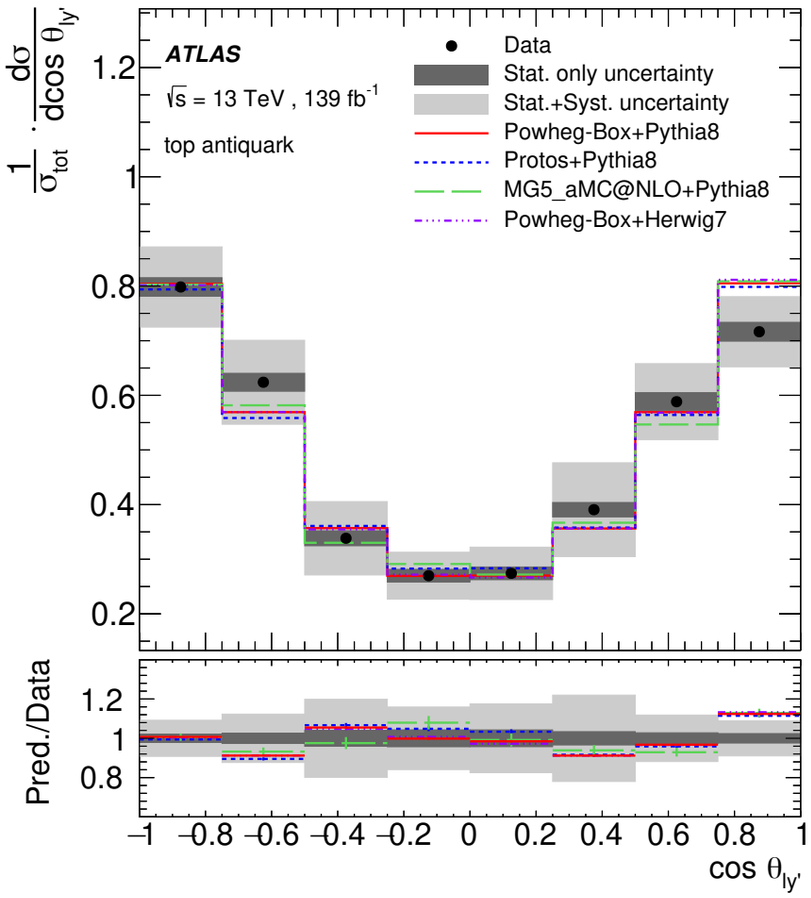


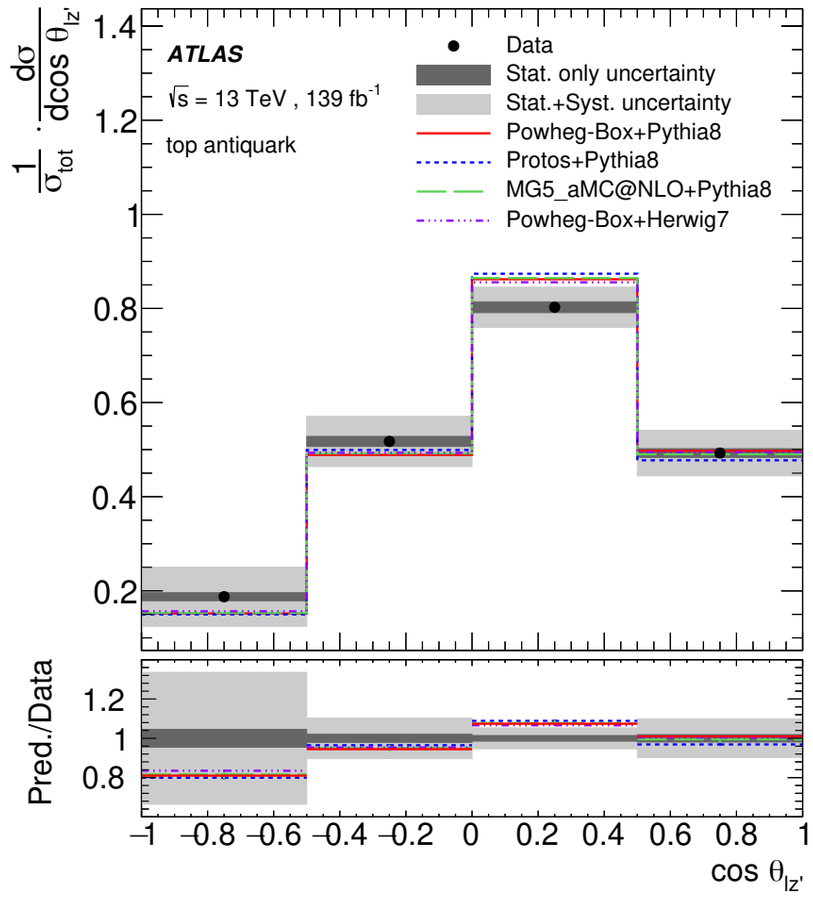




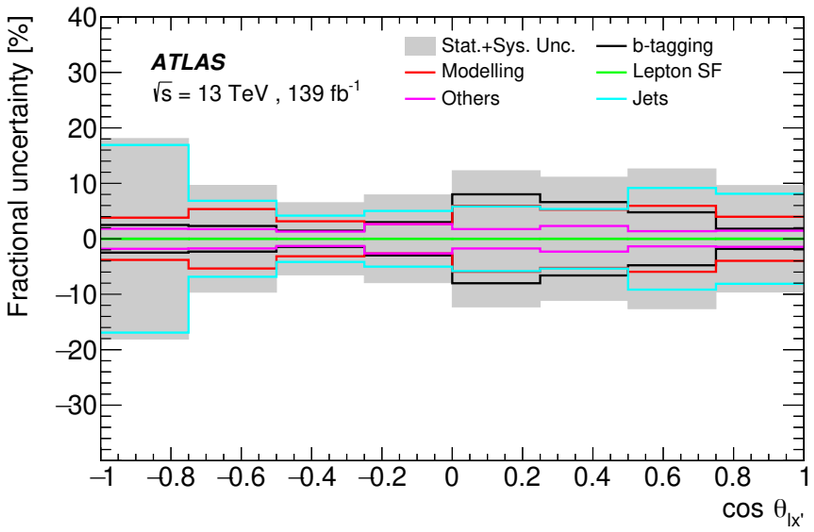
Top quark polarisation

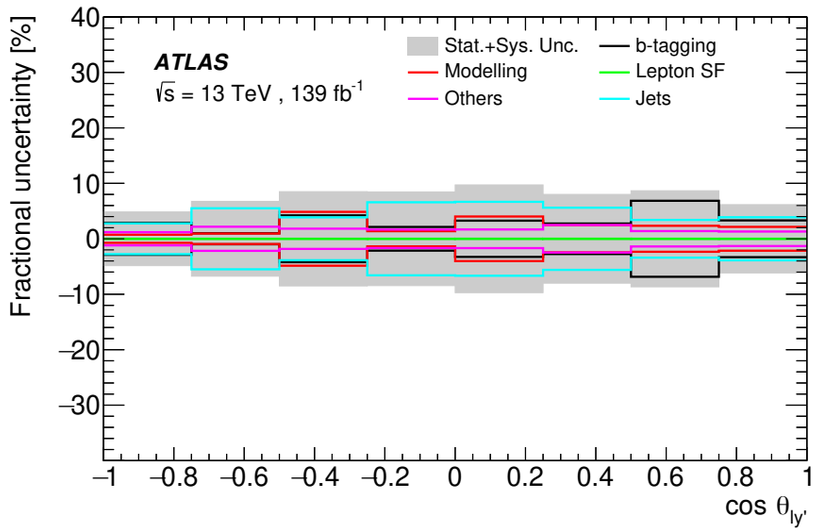


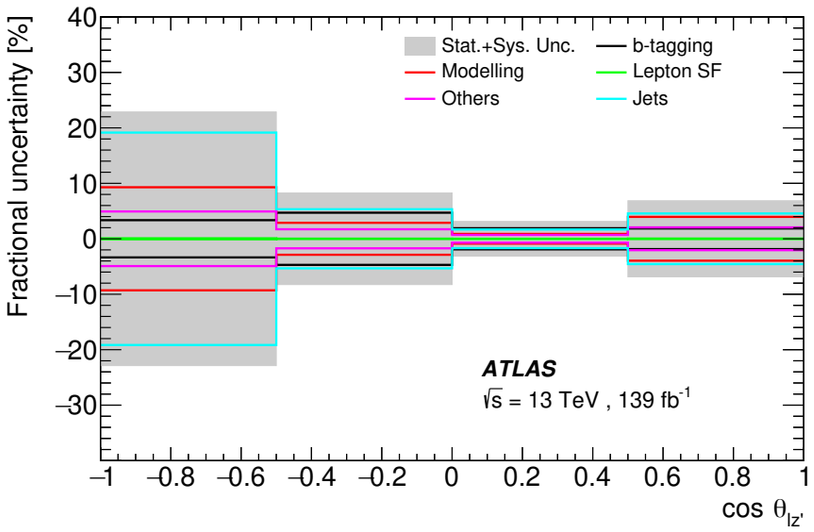


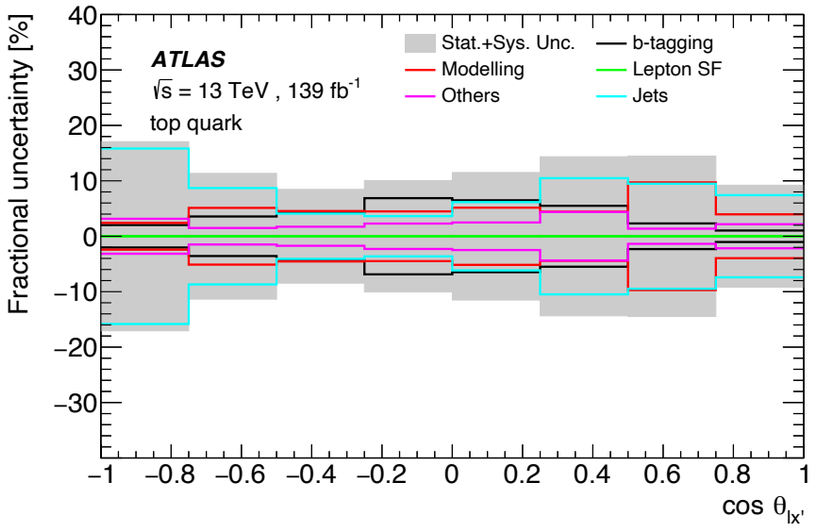


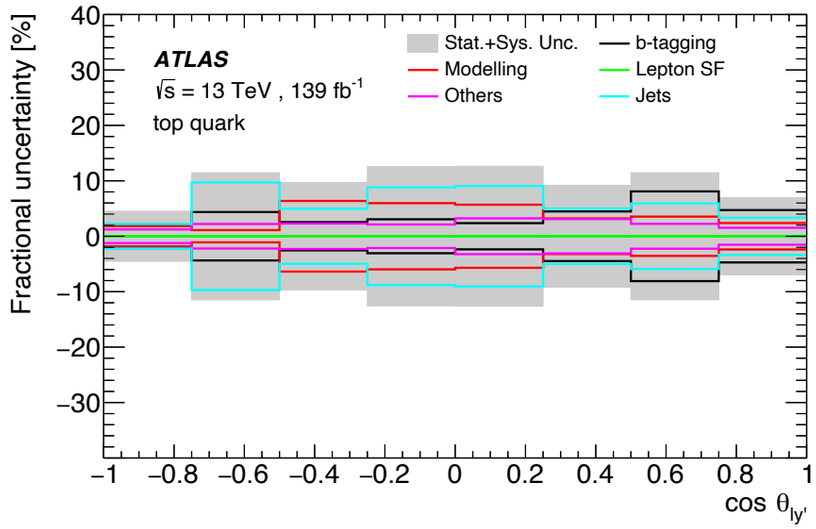
Top quark polarisation

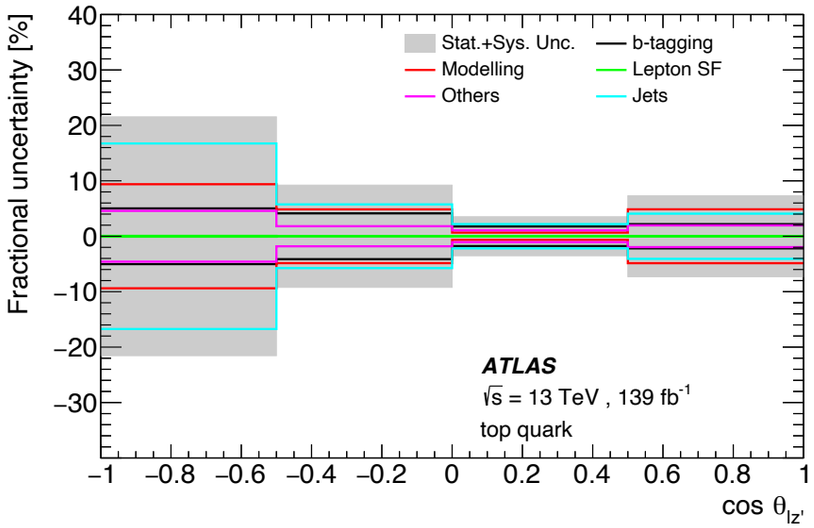


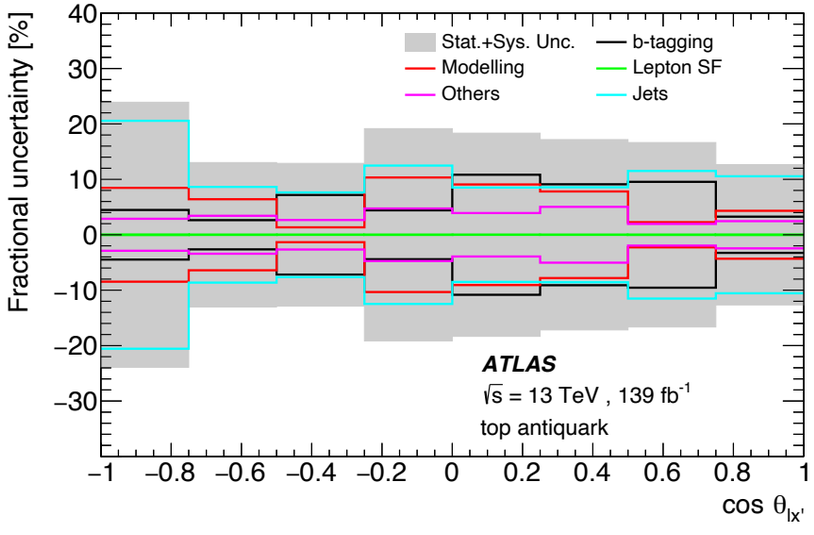


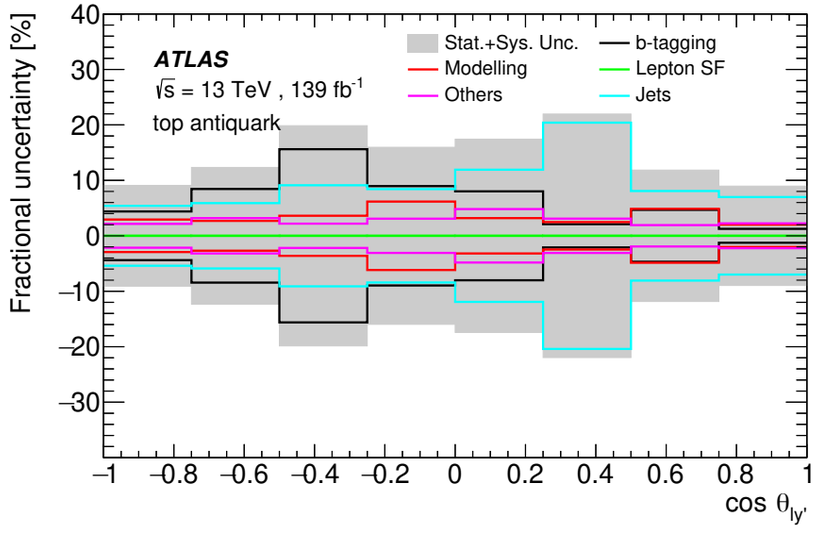


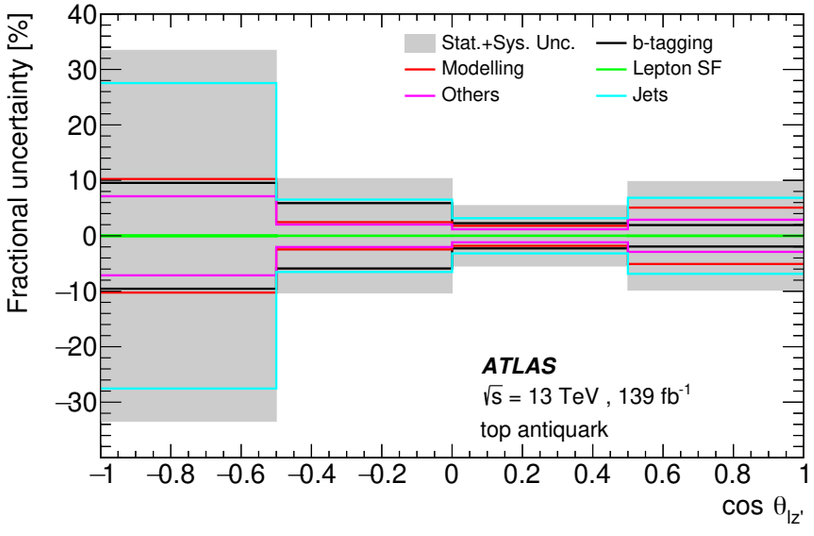




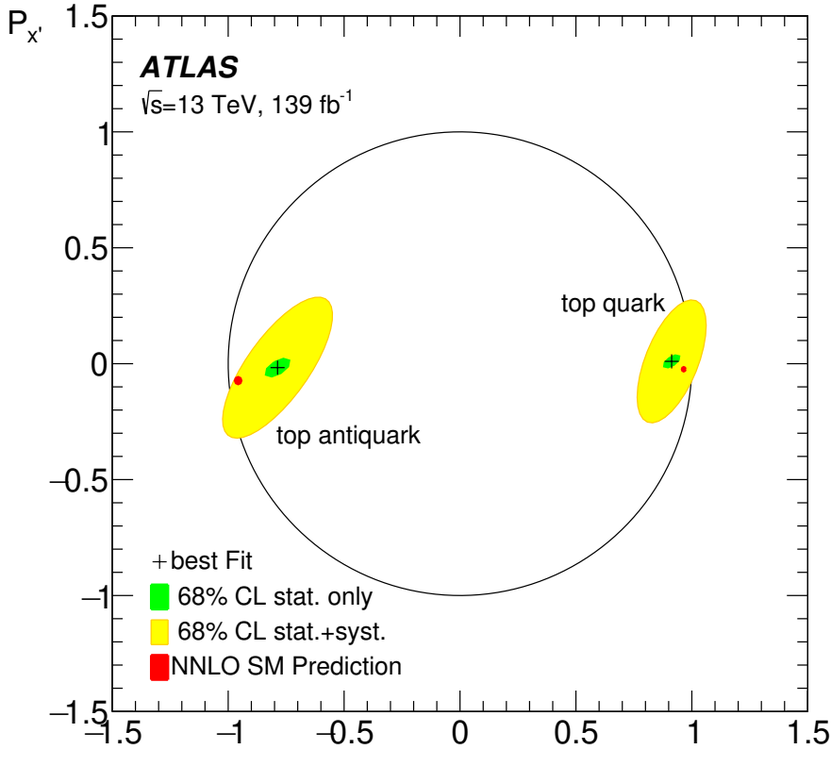


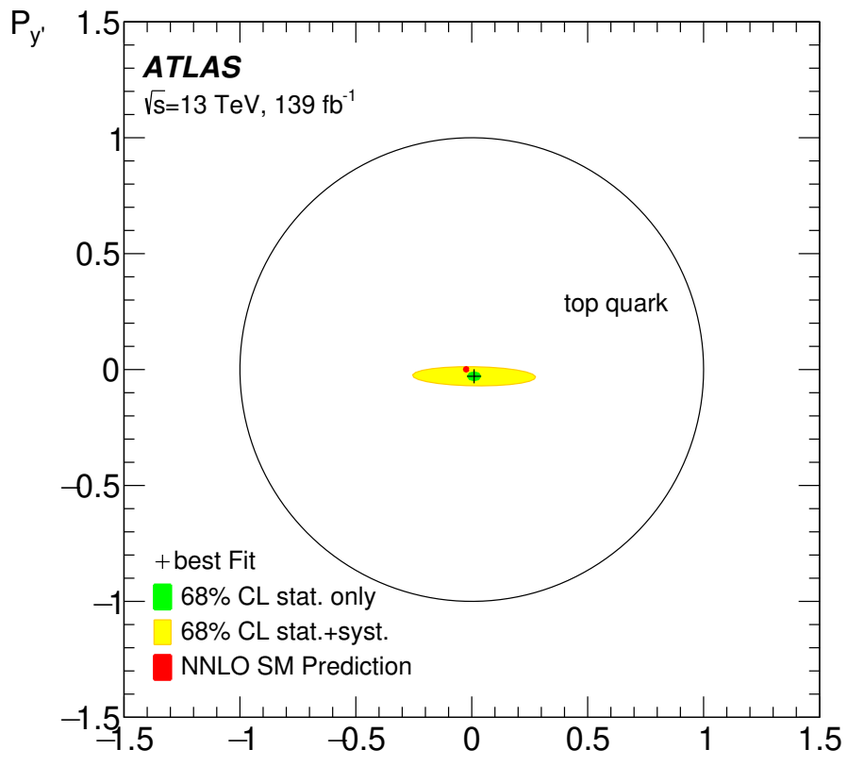


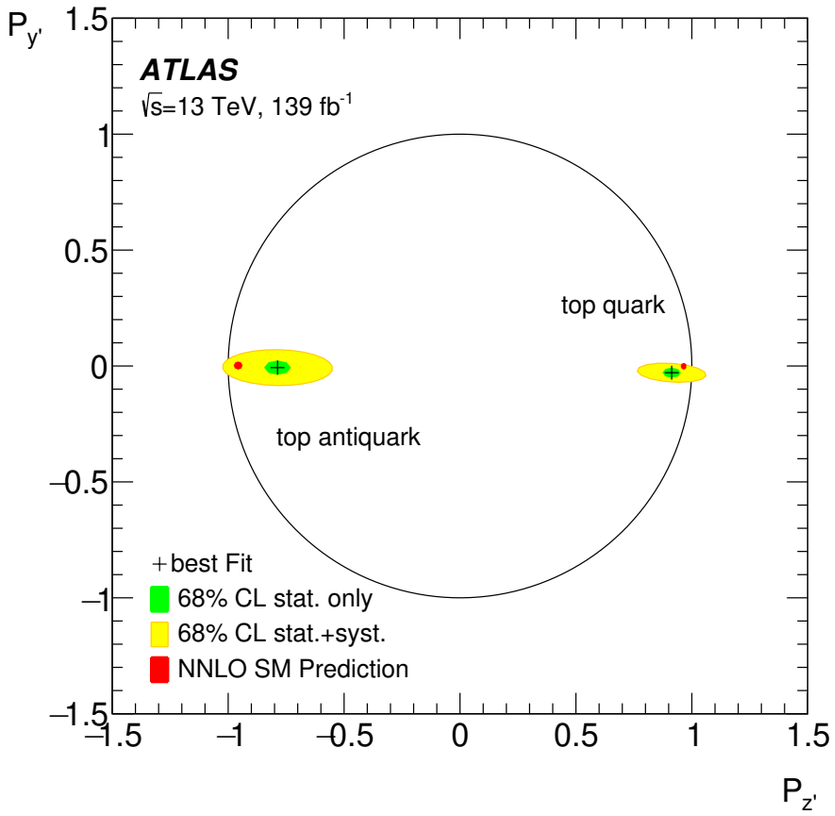


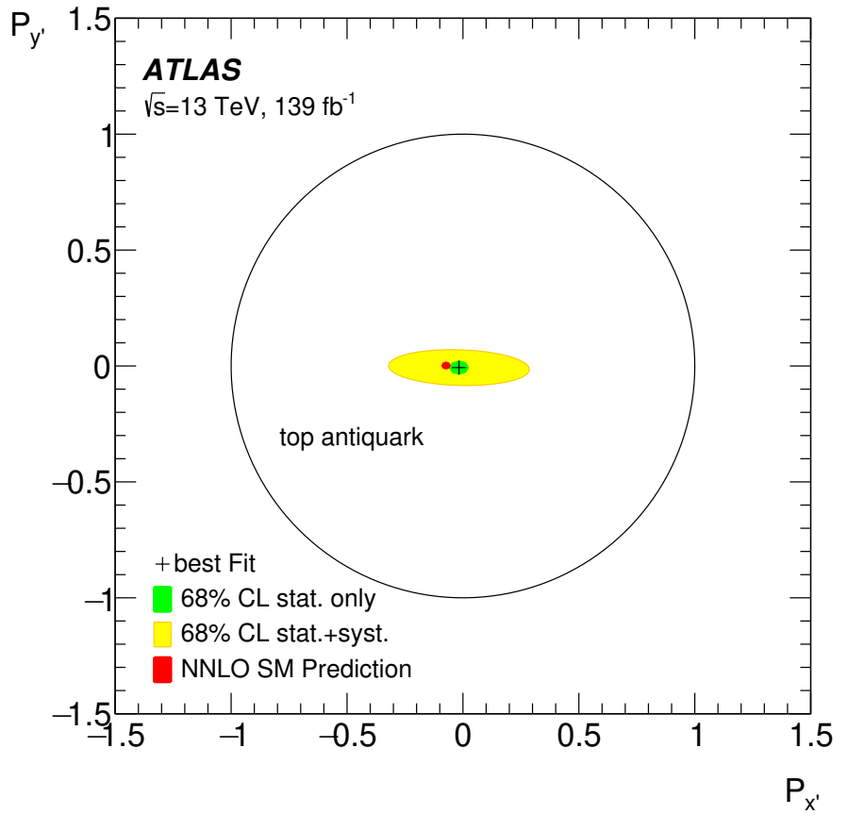


Top quark polarisation









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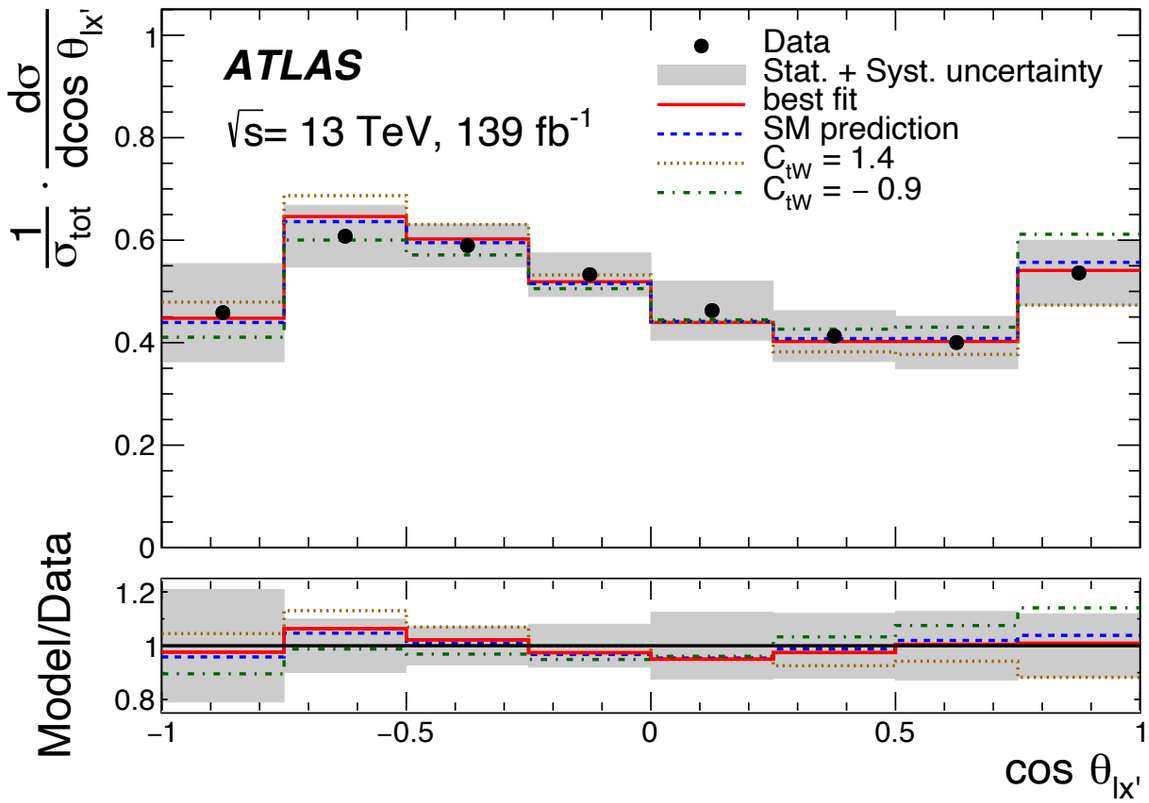
Top quark polarisation

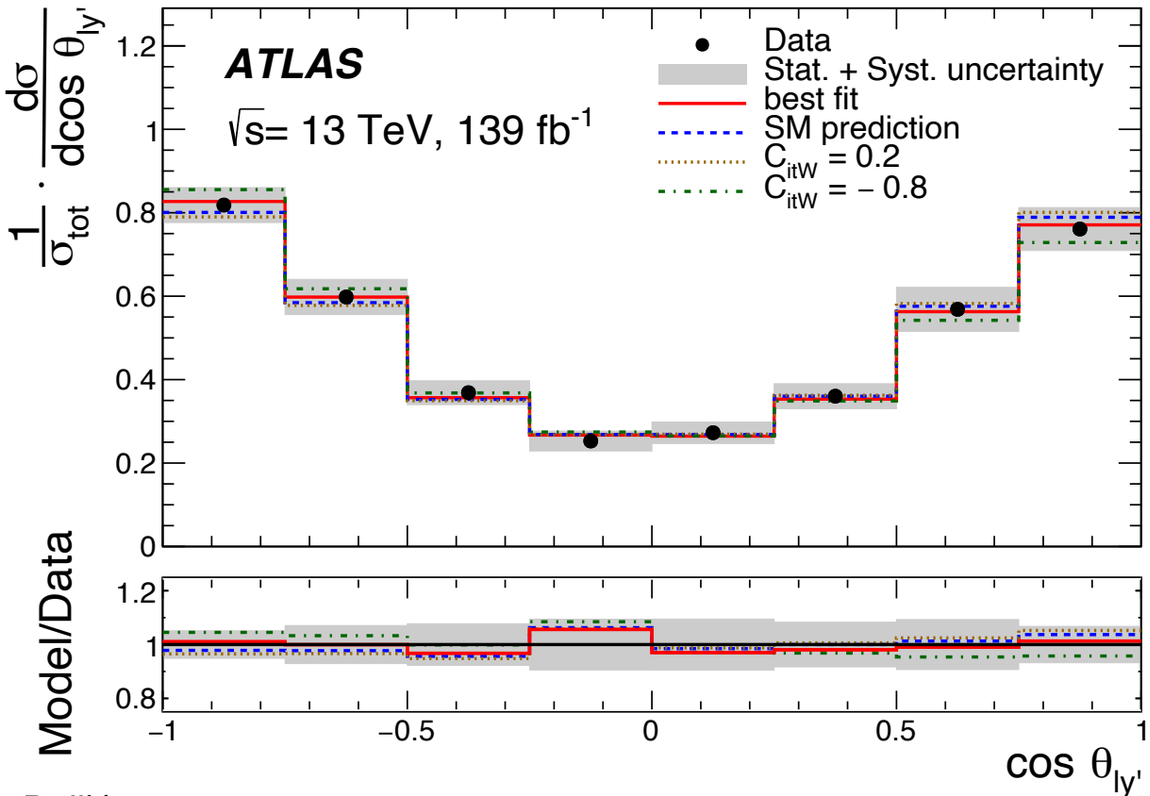
Uncertainty source	$\Delta P^{t}_{x'}$	$\Delta P^{\bar{t}}_{x'}$	$\Delta P^{t}_{y'}$	$\Delta P^{\bar{t}}_{y'}$	$\Delta P^{t}_{z'}$	$\Delta P^{\bar{t}}_{z'}$
Modelling						
Modelling (t-channel)	±0.037	±0.051	±0.010	±0.015	±0.061	±0.061
Modelling ($t\bar{t}$)	±0.016	±0.021	±0.004	±0.016	±0.003	±0.016
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

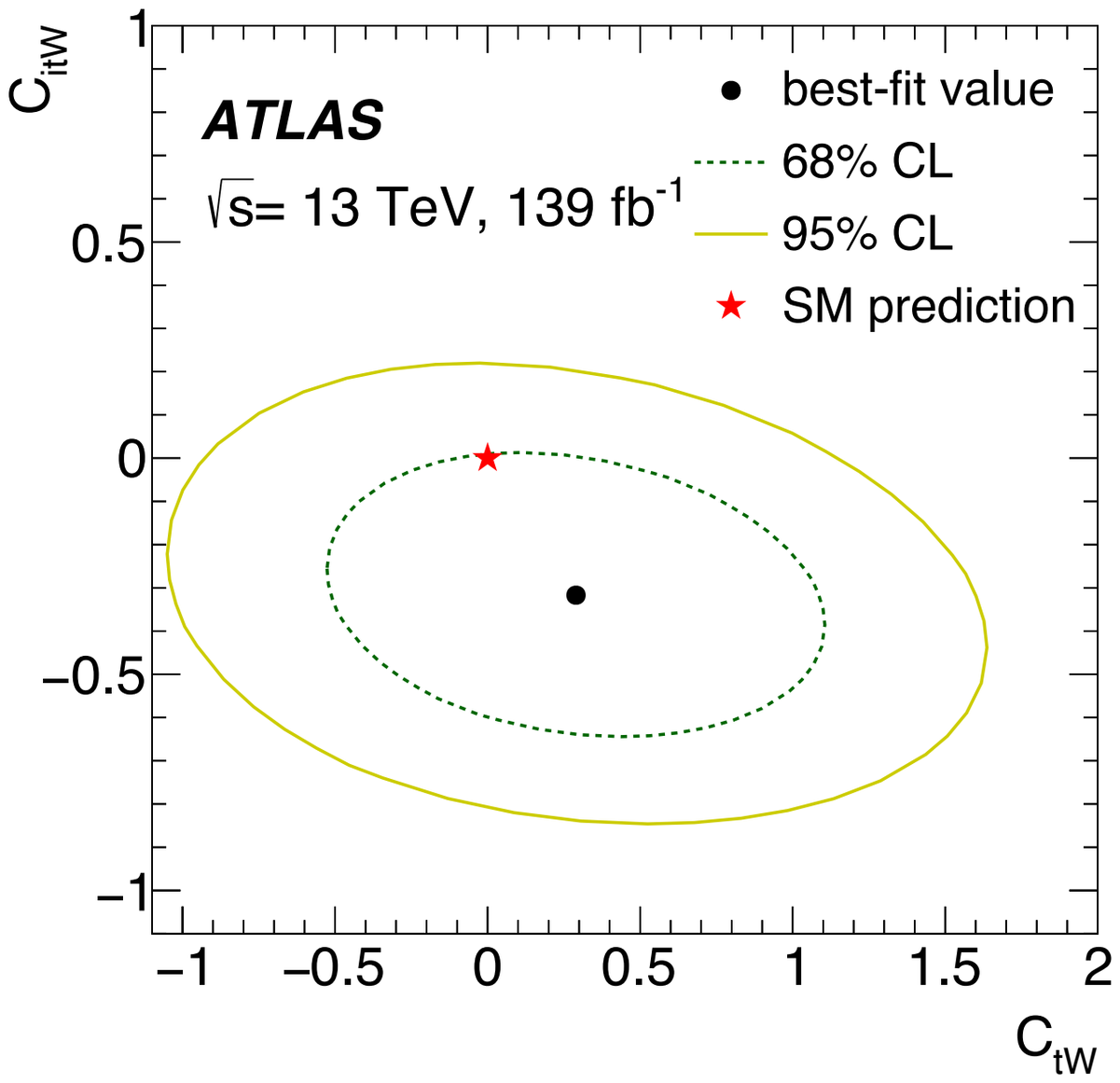
Top quark polarisation

	Top quark		Top antiquark		Top quark and antiquark	
Angular variable	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
$\cos\theta_{\ell x'}$	1.35/7	0.99	0.94/7	1.00	1.32/7	0.99
$\cos\theta_{\ell y'}$	4.57/7	0.71	2.92/7	0.89	3.78/7	0.81
$\cos\theta_{\ell z'}$	1.55/3	0.67	2.04/3	0.56	2.26/3	0.52
Global	13.55/17	0.70	6.86/17	0.99	9.25/17	0.93

Top quark polarisation







	C_{tW}		C_{itW}	
	68% CL	**95% CL**	**68% CL**	**95% CL**
All terms	[−0.3, 0.8]	[−0.9, 1.4]	[−0.5, −0.1]	[−0.8, 0.2]
Order $1/\Lambda^4$	[−0.3, 0.8]	[−0.9, 1.4]	[−0.5, −0.1]	[−0.8, 0.2]
Order $1/\Lambda^2$	[−0.3, 0.8]	[−0.8, 1.5]	[−0.6, −0.1]	[−0.8, 0.2]